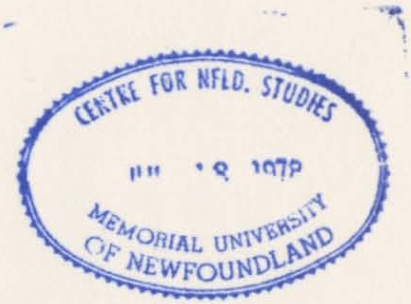
RESERVOIR QUALITY AND LATERAL VARIABILITY OF BIOTURBATED SHALLOW MARINE SUCCESSIONS

NICOLA S. TONKIN


CENTRE FOR NFLD. STUDIES
MEMORIAL UNIVERSITY
OF NEWFOUNDLAND

RESERVOIR QUALITY AND LATERAL VARIABILITY OF BIOTURBATED SHALLOW MARINE SUCCESSIONS

By

© Nicola S. Tonkin

A thesis submitted to the

School of Graduate Studies

in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

Department of Earth Sciences

Memorial University of Newfoundland

June 2011

St. John's Newfoundland

Abstract

In bioturbated reservoir facies, ichnology is integral to reservoir characterization. Ichnological analysis of a reservoir facies and subsequent classification into ichnofabrics or ichnofacies allows for characterization of reservoir properties. Bioturbation can redistribute grains and cause sorting or mixing, this physical modification of the primary sedimentary fabric causes changes to porosity, and permeability in reservoir facies. In highly bioturbated reservoir facies, bioturbation can be the first order control on petrophysical properties.

Petroleum geologists are primarily concerned with the effect that bioturbation has on the petrophysical properties of a reservoir facies, rather than the details of ichnotaxonomic identification. The proposed bioturbation style categories do not require in-depth knowledge of ichnology. The categories can easily be applied to facies and core analysis for incorporation into reservoir models. The action of bioturbators can be considered in terms of: 1) sediment mixing; 2) sediment cleaning; 3) sediment packing; 4) pipe-work building strategies; 5) combination sediment cleaning and packing; and 6) combination pipe-work building and sediment packing. Sediment packing and sediment mixing styles commonly reduce porosity/permeability, while sediment cleaning bioturbation style enhances porosity/permeability. Pipe-work building and combination bioturbation styles are highly dependent on the lithological contrast between burrow fill, and enclosing substrate. The use of bioturbation style categories, and the classification of trace fossils into these categories may be more user-friendly for reservoir geologists than existing paleoenvironmentally-driven ichnofacies or ichnofabric analysis.

While categorization of bioturbation style is a useful tool in reservoir characterization, lateral variations in reservoir quality and heterogeneity of ichnofacies or ichnofabric must be incorporated into geological models in order to predict fluid flow in bioturbated facies at the inter-well scale. Ichnological analysis allows insight into variations in sedimentation rate, hydrodynamic energy (erosive currents), substrate consistency, length of colonization window, and community succession (tiering and

cross-cutting relationships). This ichnological dataset means that inferences regarding both physical and chemical processes acting at the time of bioturbation can be made.

There is inherent ichnological variability within most bioturbated beds. The lateral variability, or patchiness of the ichnofabrics studied were not found to be related to proximity to the paleo-shoreline in the three wave-dominated depositional systems. Instead, the most critical factor appears to be the sediment accumulation style. Slow continuous deposition was found to produce complex and highly patchy ichnofabrics, whereas rapid, episodic, event bed deposition was found to be associated with the most uniform development of ichnofabric.

Autocylic and allocyclic interpretations can be postulated for bioturbated key stratigraphic surfaces in siliciclastic shallow marine settings. A case study illustrating the need for careful ichnological analysis has been undertaken as part of this thesis, and focuses on *Thalassinoides*, and its validity as an indicator for key stratigraphic surfaces. *Thalassinoides* is easily identified in core and outcrop, has a pipe-work bioturbation style, and colonizes a variety of substrates including softground and firmground (*Glossifungites* ichnofacies) substrates. The *Glossifungites* ichnofacies is commonly found in association with relative sea level change, but alternative autocyclically-generated processes should be considered. With careful ichnological investigation, realistic palaeoenvironmental and sequence stratigraphic interpretations can be made by objective consideration of both autocyclic and allocyclic processes.

This research uses bioturbated shallow marine case studies to create a first order understanding of likely reservoir quality, reservoir heterogeneity, and interpretation of candidate key sequence stratigraphic surfaces. These concepts are an integral part of reservoir to basin scale models of hydrocarbon reservoirs. With an improved, integrated, understanding of what bioturbating organisms do to sediment, ichnology can continue to grow as an important component of reservoir characterization studies, and petroleum geology in general.

Acknowledgments

Two children, one husband now a PhD submitted since arriving in Newfoundland to start my PhD in 2006, what a journey! First up, I would like to thank my wonderful husband for his enduring love and support, I love you, and your name should be on this thesis with mine. To my gorgeous boys Eddie and Lachlan, for always making me smile. Mum and Dad, thank you for your constant positivity, optimism, and far-reaching love. Hope, Lorne, Shawna, Janis and Carl thanks for all your love and support.

Thanks to the 6th floor crew; Chris, Liam, James, Pinar, Rich, Jen, Dario, Kathryn, Lise, Peter and Lina for your friendship, banter, babysitting, and good times. To Karen, Anna, and all my "Mummy" friends for keeping me sane while wrangling the midgets. Amy, Allison, Steve, Angie, Erin, Brian, Vic, Paul, Venessa, and Twyla thanks for your friendship, and always making me feel at home in St John's. Chris (Xtal), thank you for always listening, bitching with me, partying, and making me gourmet delights when I need it most. Thanks to the NZ "girls" for your never-ending, web-assisted support and love. Thank you to Kathy Campbell and Murray Gregory for giving me a solid foundation to build upon. Thank you to everyone, who I have forgotten to mention (my brain capacity has been exceeded today).

Thank you to Rudi Meyer, Elliot Burden, and my committee members Joe Macquaker and Rich Callow for your support. To my supervisor and friend Duncan McIlroy, thank you for your guidance, support, and for putting up with my double maternity leave!

Table of Contents

List of Tables

List of Figures

Co-authorship Statement

The following chapters are presented in manuscript format. Each chapter/manuscript has already been, or will be, submitted to an international scientific journal. Consequently, these works have involved collaboration with other authors. I shall describe below the work personally done and contributions made by my co-authors. In each case the work is predominantly my own, completed with collaboration, guidance and editorial advice from my supervisor and co-author Duncan McIlroy, and other junior collaborators.

The first manuscript (Chapter 2, Tonkin *et al.*, 2010) is a core-based study. Core-logging was undertaken by me in May 2008 at CNLOPB core storage. Core slabs had been previously collected by my co-authors Rudi Meyer and Allison Turpin. Rudi Meyer trained me in use of the probe permeameter and provided guidance in this area. Permeability measurements and visual estimation of porosity were undertaken by me. Blue-epoxy impregnated thin sections were prepared by Calgary Rock Sales. I am the primary author on the manuscript with my supervisor Duncan McIlroy and co-author Rudi Meyer providing guidance and constructive editorial comments. This work was funded by an NSERC Discovery Grant and an NSERC/PRAC CRD Grant to Duncan McIlroy, with supplementary funding from the Pan-Atlantic Petroleum Systems Consortium.

The second case-study based manuscript (Chapter 3), involved data collected from 3 outcrop localities. Field seasons in Argentina, New Zealand and Utah were completed in 2006. All data was collected by me (logs and sampling), with rock-saw assistance from Duncan McIlroy. CT scanning was done by Chris Phillips. Preparation of large thin slices was done by Chris Phillips and Leon Normore. Blue-epoxy impregnated thin sections were prepared by Calgary Rock Sales, and standard thin sections provided by the technicians at MUN. Duncan McIlroy provided expert knowledge, guidance, and editorial comments during construction of the manuscript. Funding came from a NSERC Discovery Grant to Duncan McIlroy.

The third manuscript (Chapter 4) is a conceptual study, with examples from outcrop and core-based study of *Thalassinoides* burrows collected throughout my PhD.

Specimens were observed and/or collected by me from offshore Newfoundland (core slab), New Zealand (slab sample and observation), Argentina (observations), and Utah (observations). All images logs, images were personally acquired. Duncan McIlroy provided guidance and constructive editorial comments. Funding came from the NSERC Discovery Grant to Duncan McIlroy.

Chapter 1: Introduction

Many of the world's siliciclastic reservoirs are developed in bioturbated shallow marine facies including Jeanne d'Arc Basin, offshore Newfoundland, Canada; North Sea, UK; Halten Terrace, offshore mid-Norway; Athabasca Oil Sands, Canada; and Orinoco Oil Belt, Venezuela (McAlpine, 1990; Richards, 1992; Cannon and Gowland, 1996; McIlroy, 2004b; Crerar and Arnott, 2007; Labourdette et al., 2008). Bioturbation can redistribute grains and result in either sorting or mixing; this physical modification of the primary sedimentary fabric affects porosity and permeability in reservoir facies. Effective production of hydrocarbon reservoirs requires reliable prediction of facies-related reservoir properties and correlation at the inter-well scale. In bioturbated facies, paleoenvironmental analysis and reservoir characterization are heavily reliant upon the description and interpretation of ichnofabrics (e.g., Martin and Pollard, 1996; Pemberton *et al.*, 2001; McIlroy, 2004b; Pemberton and Gingras, 2005; Gingras *et al.*, 2007; Tonkin *et al.*, 2010).

In this thesis, outcrop and core-based case studies are used to produce a first order understanding of: 1) the effect of bioturbation on reservoir quality; 2) lateral ichnological variability; and 3) the interpretation of "*Glossifungites* surfaces" that may be incorporated into paleoenvironmental and reservoir models of siliciclastic shallow marine hydrocarbon reservoirs.

1.1 Aim and Scope

This research generates a more complete understanding of the impact that bioturbation has on reservoir quality and characterization of shallow marine successions. Bioturbated siliciclastic strata are studied: 1) at the micro-fabric scale; 2) the outcrop scale; and 3) in terms of sequence stratigraphic cycles. The aim at the micro-fabric scale is to understand the role that organisms have in controlling the porosity and permeability of sandstone reservoir intervals. Along-strike or lateral trends in sedimentological and ichnological variability are studied at the outcrop scale. This work also considers autocyclic and allocyclic processes inherent to producing the *Glossifungites* ichnofacies and bioturbated key stratigraphic surfaces. Shallow marine case studies from New Zealand, Utah, Argentina, and offshore Newfoundland are used to achieve these aims. Development of a consistent quantitative methodology is required in order to objectively compare sedimentological and ichnological datasets. This research into shallow marine bioturbated reservoir intervals is innovative in its quantitative style (inclusion of porosity and permeability data), identification of multiple autocylic and allocyclic interpretations for "*Glossifungites* surfaces", documentation of lateral trends in ichnofabric from deltaic facies, and proposal of simple bioturbation style categories that can be used as a tool in reservoir quality prediction.

Samples from reservoir facies were taken along vertical and lateral profiles of bioturbated sandstone successions. This thesis uses detailed ichnological analysis, facies analysis, logging of outcrop, petrography, permeability/porosity measurements,

and large thin slicing to produce and refine the reservoir characterization of bioturbated facies.

1.1.1 Objectives

1) Describe the physical modifications that trace fossils cause to sediments and sedimentary rocks, compared to the original primary unbioturbated fabric.
    a. Ichnological and facies analysis of studied outcrop and core, including logging of section/core, and large thin slicing of slab samples.
    b.Qu antify bioturbation in terms of petrophysical properties (porosity and permeability). Measure permeability of slabs (on cm-scale) and visually estimate porosity from thin sections.
2) Describe the relative heterogeneity of ichnological and sedimentological properties along horizontal (lateral) transects, and consider the implication of this variability for ichnologically based facies modeling.
3) Describe the environmental and depositional history of *Thalassinoides*-bearing surfaces recorded in ichnofabrics, considering both autocyclic and allocyclic mechanisms for formation and preservation.
4) Erect bioturbation categories that quantify the physical modifications that trace-makers produce in siliciclastic facies, for use in predicting reservoir quality.

1.2 Bioturbation

Trace fossils are biogenic sedimentary structures, tracks, trails and borings produced by animals on or within the sediment or rock (Häntzschel, 1975; Bertling *et al.*, 2006). Trace fossils record fossil behaviour, effectively the response of organisms to the physical, biological, and chemical environments in which they lived (Figure 1.1). Integrating sedimentology and ichnology results in more comprehensive paleoenvironmental reconstructions, including physico-chemical parameters, and aids in the identification of key stratigraphic surfaces (see reviews in Taylor *et al.*, 2003; Gingras *et al.*, 2011). Ichnological analysis provides insights into some aspects of ancient environments (e.g., salinity and relative oxygenation) that cannot be gleaned from the study of physical sedimentary structures alone (Ekdale and Mason, 1988; Savrda and Bottjer, 1991). Studying the effects of bioturbation is important in understanding the dynamic processes associated with sedimentation in shallow marine settings.

1.3 Paleoenvironmental controls on trace fossil distribution

The main paleoenvironmental controls on bioturbation are: sedimentation rate, salinity, turbidity, oxygenation, substrate consistency, hydrodynamic energy, and event bed deposition (see reviews in Taylor *et al.*, 2003; McIlroy 2004a; Gingras *et al.*, 2011). Physico-chemical parameters that affect bioturbation include grain size, turbidity, light, temperature, and sediment supply; while biological constraints include

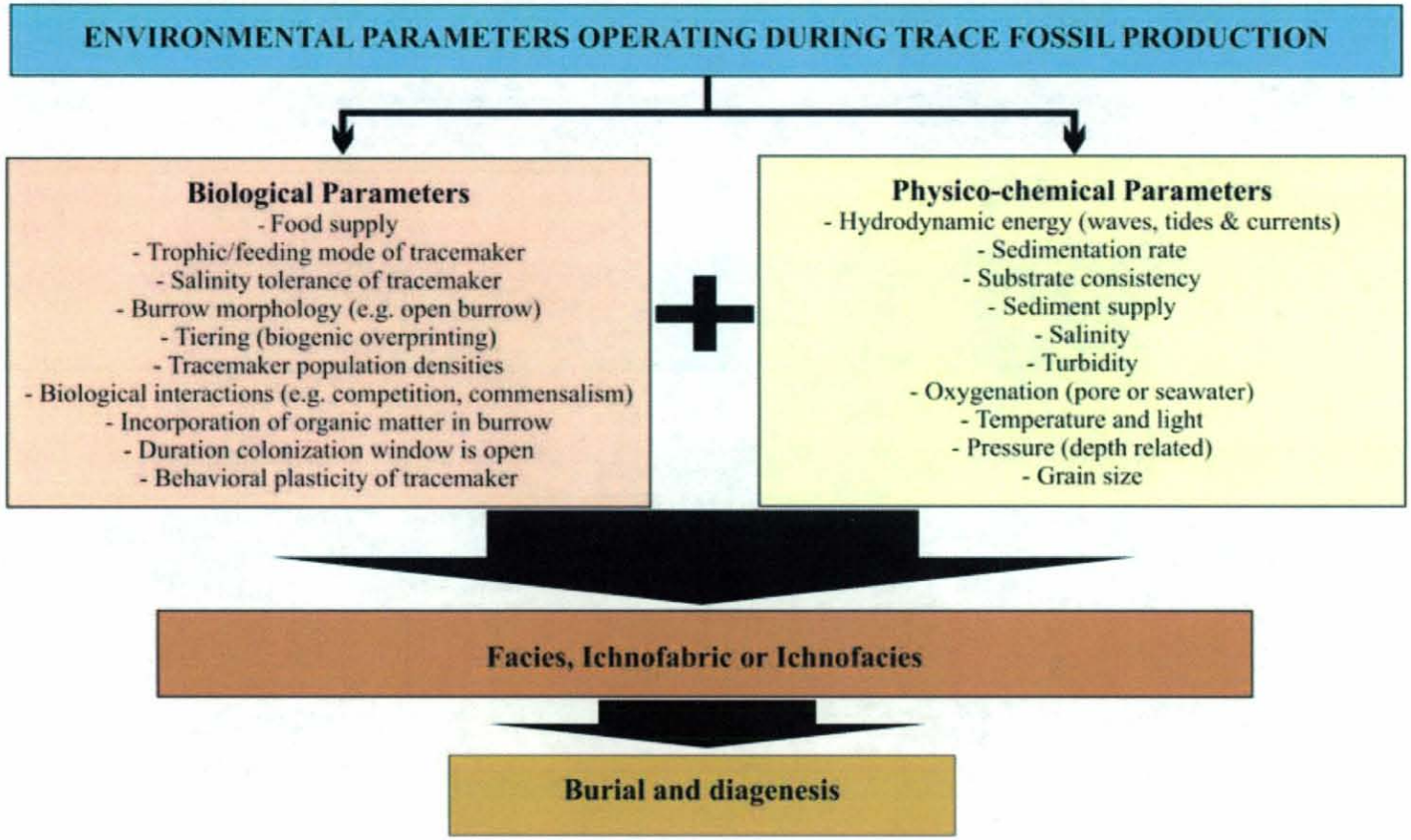


Figure 1.1. Environmental controls on trace fossil production. Note feedbacks exist between the physico-chemical parameters and biological parameters.

salinity tolerance of the tracemaker, food supply and burrow morphology (Figure 1.1). Reworking of sediments at the coastline by physical processes controls the bioturbation intensity, diversity and ichnological distribution in shallow marine settings. The following subsections detail the physical and biological parameters that control the distribution, diversity, and abundance of trace fossils in shallow marine environments (Figures 1.1 and 1.2).

1.3.1 Hydrodynamic energy and bioturbation

The distribution of trace fossils is linked to hydrodynamic energy in all depositional settings. The dominant hydrodynamic processes that actively erode, transport, or deposit sediment in shallow marine settings are fluvial currents, hyperpycnal flows, tidal currents, longshore wind-generated currents, wave- and storm-induced gravity flows, and turbidity currents (see review in Nittrouer and Wright, 1994). The shoreface and proximal delta front are high hydrodynamic energy settings with rapid sedimentation rates. Shallow marine facies are typically well-sorted and sand-rich (Reading and Collinson, 1996), and are associated with enhanced porosity and permeability. Consequently, the distribution of reservoir properties with regard to geometry and architecture is of particular interest in hydrocarbon reservoir characterization (e.g. Brandsæter *et al.*, 2005; Howell *et al.*, 2008; Ainsworth *et al.*, 2011). Upper shoreface and proximal delta front facies are typically characterized by low bioturbation intensities and low ichnological diversities. Typical trace fossils that can be found in the high-energy environments such as the upper shoreface, and proximal delta front deposits are vertical burrows including *Diplocraterion*, *Ophiomorpha*, *Skolithos*, and *Arenicolites* (e.g., Gingras *et al.*, 1998; McIlroy *et al.*,

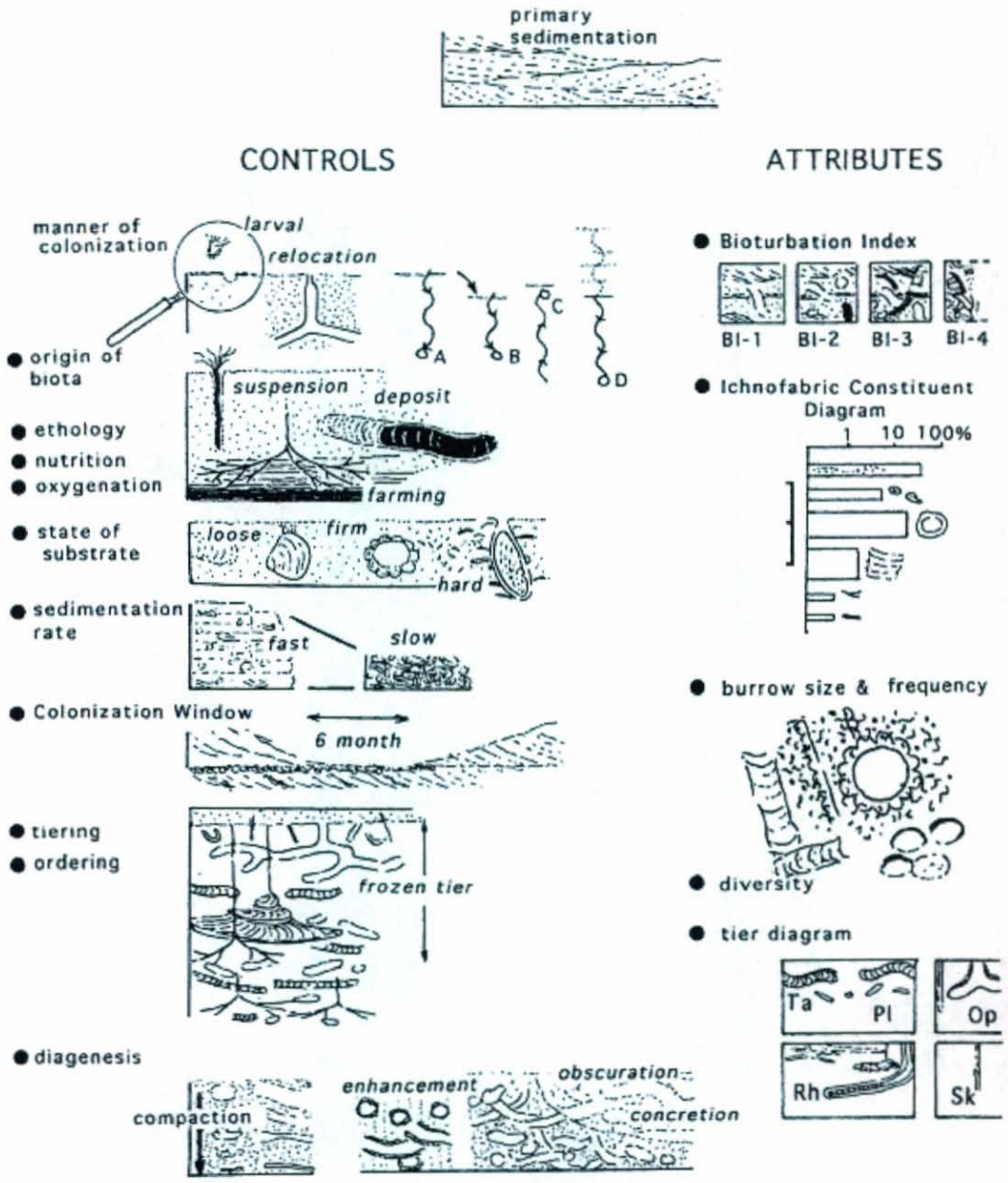


Figure 1.2. Summary figure showing the various controls (left) and attributes (right) of an ichnofabric, from primary sedimentation to diagenesis (taken from Taylor *et al.*, 2003).

2005). As such, the deposits have an ichnological assemblage comparable to the *Skolithos* ichnofacies (Seilacher, 1964; 1967a; Bromley and Asgaard, 1991; MacEachern *et al.*, 2007c).

Trace fossil diversity and intensity of bioturbation generally increase both offshore and laterally away from sources of high sedimentation input such as distributary channel mouths. Facies with low sedimentation rates or event-bed type sedimentation patterns (e.g., lower shoreface, distal delta front to prodelta, and shelf settings) are typically characterized by moderate to high bioturbation intensity and trace fossil diversity. Overprinting of ichnocoenoses (i.e. palimpsesting) is common where sedimentation rate is low.

In the moderate energy facies of the delta front, lower shoreface, and the inner-shelf, deposits are dominated by a mix of vertical and horizontal trace fossils including *Teichichnus*, *Asterosoma*, *Ophiomorpha*, *Thalassinoides*, and *Planolites* (broadly equivalent to the *Cruziana* ichnofacies; Gingras *et al.*, 1998; Cumming *et al.*, 2006; Buatois *et al.*, 2008). In low to variable energy facies including prodelta, offshore transition zone below storm-wave base, and in the outer shelf, deposits typically contain *Phycosiphon*, *Chondrites*, *Zoophycos*, and *Scolicia* (equivalent to the *Cruziana* and *Zoophycos* ichnofacies; Pemberton *et al.*, 2001; Wetzel and Uchman, 2001).

1.3.2 Salinity tolerance of trace-making organisms

The salinity characteristics of marine systems can be broadly grouped into: 1) normal marine, 2) brackish and fresh-water environments. Biological diversity and organism size are thought to co-vary with salinity (Pickerill and Brenchley, 1991;

Pemberton *et al.*, 1992; Gingras *et al.*, 2011). Rapid salinity fluctuations are somewhat buffered in pore-water systems due to slow rates of diffusion (see discussion in McIlroy, 2004a). Infaunal biomineralized organisms have behavioural adaptations to protect against short term osmotic stress caused by rapid salinity change (reviews in Buatois *et al.*, 1997; McIlroy, 2004a; Gingras *et al.*, 2011). Ichnological assemblages of fresh-water environments are usually devoid of complex feeding burrows (e.g. *Mermia* ichnofacies; Mángano and Buatois, 2004). Brackish water or marginal marine assemblages are characterized by simple horizontal and vertical burrows including *Planolites*, *Diplocraterion*, *Skolithos*, *Palaeophycus*, *Lockeia*, and *Thalassinoides* (Buatois *et al.*, 2005). In these ichnological assemblages, salinity is seldom demonstrably the first order control on ecology (temperature, sedimentation rate, substrate consistency and turbidity are generally all involved; McIlroy *et al.*, 2004b; Buatois *et al.*, 2005).

Fluvial, brackish, and marine assemblages have distinct ichnological assemblages. Some ichnotaxa are seemingly ubiquitous such as *Planolites* which is considered to have been made by euryhaline organisms (Mángano and Buatois, 2004). Low diversity assemblages interpreted as being made by euryhaline organisms are commonly considered to be indicative of brackish water settings (Mángano and Buatois, 2004). An integrated approach incorporating careful sedimentary facies and ichnological analysis is required. Persistently brackish paleoenvironments are only really expected in distributary channels, near-channel paleoenvironments and potentially in restricted seas, lagoons, estuaries and fjords (cf. Martinius *et al.*, 2001; McIlroy *et al.*, 2005; Dalrymple, 2010).

1.3.2.1 Saline Wedge

Less dense fresh-water sits above saline water in some estuarine systems (Dalrymple *et al.*, 1992). The density contrast between essentially fresh-water in distributary channels—with varying proportions of suspended sediment load—relative to the saline waters of the marine basin controls the mode of sediment dispersal processes at the river mouth (Wright, 1977). The salt-water wedge, and the associated fine-grained suspended sediment to the turbidity maximum zone can extend landward into the delta plain, trapping silts and clays in the nearshore zone until fluvial discharge is high enough to push the sediment-laden wedge seaward, and into the receiving marine basin (review in Dalrymple and Choi, 2007). As a consequence of this salinity wedge, marine influence from the receiving basin can extend into the marginal marine realm of inner estuary, distributary channels and delta plain facies (Dalrymple, 2010).

The salinity wedge is critically important in ichnological analysis of tide-dominated ancient deltaic and estuarine successions, as it can create significant along-strike and up-dip variability of ichnofabrics (e.g., Gingras *et al.*, 1999; Mángano and Buatois, 2004; McIlroy, 2004b; McIlroy *et al.*, 2005; Fielding, 2010). Fluvial influence can also extend seaward of the distributary mouth as hypopycnal, homopycnal or hyperpycnal flows (Wright, 1977; Brettle *et al.*, 2004; Bhattacharya and MacEachern, 2009; Macquaker *et al.*, 2010a).

1.3.3 Sedimentation rate and the colonization window

The deceleration of fluvial or marine currents can cause rapid deposition of the suspended sediment load, as can flocculation in the mixing zone of estuaries (Pryor,

1975, McIlroy, 2004b; Boyd *et al.*, 2006). Sedimentation rate is variable, from instantaneous and permanent deposition to erosion and redistribution by waves and tides, sometimes in a multi-cyclic fashion (Einsele *et al.*, 1991). Rates of sediment deposition and reworking are to a large degree controlled by: 1) depositional setting (particularly water depth); 2) hydrodynamics of the receiving basin (Orton and Reading, 1993); and 3) destruction/generation of accommodation space by both autocyclic and allocyclic processes (Van Wagoner *et al.*, 1988; Einsele *et al.*, 1991).

In order to assess the paleoenvironmental significance of a highly bioturbated bed or bedset, it is important to be able to compare the intensely bioturbated unit with its "normal" counterpart (Figure 1.2). In shallow marine successions, some facies are persistently highly bioturbated indicating persistently low rates of sedimentation relative to the rate of bioturbation (Chapter 3). Preservation of physical sedimentary structures within a bed is a function of sedimentation rate, bioturbation rate, and bed thickness (Wheatcroft, 1990; Bentley and Sheremet, 2003). This window of opportunity on the seafloor for bioturbation of the substrate (and potential obscuring or destruction of primary sedimentary fabric) is known as the colonization window (Pollard *et al.*, 1993; Figure 1.2). Environmental stability can be reflected in the length of time that the colonization window is open (Taylor *et al.*, 2003).

Shallow marine facies have highly variable sedimentation rates (Walker and James, 1992). Successions characterized by rapid continuous sedimentation are commonly devoid of trace fossils or are sparsely bioturbated, by low diversity ichnological assemblages, with optimal preservation of primary sedimentary fabrics (e.g. lower shoreface Neslen Formation, Chapter 3). In areas of slow continuous sedimentation, bioturbation intensity and ichnodiversity are commonly high (e.g.

shelfal Pohutu Formation, Chapter 3). This is due to the colonization window being open long enough for biogenic reworking of sediments. Facies with such low net accumulation rates, and repeated overprinting may be characterized by intense bioturbation, which obscures/destroys most primary sedimentary structures (Taylor and Goldring, 1993).

Fluvial input to the marine basin, and generation of sediment gravity flows can be seasonally variable. The inter-bedding of fair-weather and event-bed deposits, may produce "lam-scram" fabrics of alternating low ("lam" or laminated) to high ("scram" or scrambled) intensities of bioturbation (Howard, 1972). The thickness of an event bed is an important limiting factor on benthic ecology, as it may smother existing infaunal communities, effectively causing macrofaunal defaunation if the endobenthos are unable to escape to the new sediment-water interface (Pollard *et al.*, 1993; Wheatcroft and Drake, 2003). If colonization from below is not possible, post-depositional re-colonization by juveniles or adult organisms is possible (McIlroy, 2004a), though the new seafloor substrate may not be initially entirely hospitable to deposit feeding organisms due to a lack of deposited organic matter (see discussion in Herringshaw *et al.*, 2010).

1.3.4 Oxygenation

The oxygenation of interstitial pore-waters at the sediment-water interface is a relatively common first order control on trace fossil distribution in subaqueous environments (Savrda and Bottjer, 1991). Well-oxygenated seafloors will typically exhibit high degrees of bioturbation, and burrowing to depth below the ancient seafloor. The maximum depth of burrowing and infaunal colonization of shallow,

mid-, and deep-tiers (i.e., the vertical partitioning of substrate; Berger *et al.*, 1979; Ausich and Bottjer, 1982) or mixed and transition layers (Goldring, 1995; Bromley, 1996) can be used as an indicator of well-oxygenated bottom waters and pore-waters (Bromley and Ekdale, 1984; Bromley, 1996; Figure 1.2).

Some marginal marine and delta plain environments may be rich in sedimentary organic matter (e.g., swamps, tidal flats, marshes, lagoons and bay fills; Reading and Collinson, 1996). Increased accumulation of organic carbon-bearing sediment at or near the sediment-water interface can result in higher microbial productivity using free oxygen which can lead to locally oxygen-poor, pore-water environments (Jørgensen and Postgate, 1982; Konhauser and Gingras, 2007). Endobenthic activity in such organic-rich sediments is seldom limited by the absence of pore-water oxygen. Oxygenated waters can be introduced to the sediment by bioirrigation, which also stimulates microbial growth in the near-burrow environment (Gust and Harrison, 1981; Herringshaw *et al.*, 2010) or simply by maintaining a connection to the sediment-water interface while feeding on sediments below the redox boundary (see discussion of sulphur mining in echinoderms by Bromley, 1996). Tidal flat facies containing solely *Ophiomorpha* or *Thalassinoides* traces may be indicative of a periodically oxygen stressed paleoenvironment where pore-water oxygenation fluctuate through the tidal cycle (Swinbanks and Lutternauer, 1987).

Shoreface, deltaic and shelf facies are areas of dynamic coastal processes and are characterized by strong bottom currents (Reading and Collinson, 1996). These currents are commonly a combination of fluvial, wave and tidal processes, which keep the water column mixed, and the bottom water oxygenated, making it suitable for endobenthic/trace-making organisms. Consequently, bottom-water oxygenation in

shallow marine settings is not generally a controlling factor in the occurrence and distribution of shallow marine trace fossils. This is particularly true of the shallow marine facies focussed upon in this thesis.

1.3.5 Substrate consistency and bioturbation

Shallow marine substrates are commonly found to be softgrounds, with occasional soupground, firmground and woodground substrates (Seilacher, 1978; Ekdale, 1985; Goldring, 1995; Figure 1.2). Bioturbated softground substrates are typically depositional settings with continuous deposition, or hiatuses (see Chapter 4 for discussion). Bioturbated firmground substrates can also be interpreted as a hiatal surfaces (e.g., "*Glossifungites* surfaces"; Gingras *et al.*, 1999, 2007). Firmground surfaces in shallow marine settings may typically be colonized by *Thalassinoides* and have autocyclic (e.g., change in sediment delivery) or allocyclic (e.g., eustatic sea-level fluctuations) causative mechanisms. Soupgrounds are generally found in association with rapid deposition, especially where rapid flocculation in the mixing zone, or remobilization of partly settled mud by waves and tidal currents produces hyperpycnal flows, and fluid mud deposition (Bentley and Nittrouer, 2003; Bhattacharya and MacEachern, 2009; Macquaker *et al.*, 2010a).

1.3.6 Nutrients and feeding mode of the tracemaker

Organic nutrients are not typically a limiting resource in shallow marine depositional environments. This is evident in the presence of particulate organic matter in most shallow marine sandstones and mudstones (Macquaker *et al.*, 2010b).

Organic matter availability is not considered to be a limiting factor in the ecology of most benthic marine systems. Organic particulates from terrestrial and marginal marine vegetation are commonly rich in refractory organic compounds (Gooday *et al.*, 1990). Many shallow marine trace fossils (e.g. *Arenicolites*) are thought to culture micro-organisms on buried detrital organic matter, processing the microbial biomass for food (see Bromley, 1996; Herringshaw *et al.*, 2010). Bioavailable organic matter is commonly present both in suspension and buried in sediments. The trace fossil assemblages found in shallow marine facies are likewise inferred to represent a mixture of suspension, gardening, scavenging and deposit feeding behaviours (Nickell and Atkinson, 1995; McIlroy, 2004b; MacEachern *et al.*, 2007b; Herringshaw *et al.*, 2010).

While trace fossil morphology does reflect behaviour of the trace-maker, the feeding strategy of the tracemaker is commonly more complex. Recent research has demonstrated that number of modern benthic burrowing organisms display significant behavioural plasticity, with a single burrow serving multiple purposes (e.g., thalassinid shrimps, Suchanek, 1985; Nickell and Atkinson, 1995; Herringshaw *et al.*, 2010).

1.3.7 Summary of paleoenvironmental controls on ichnology

Shallow marine settings are generally sites of abundant food supply, well-oxygenated water columns and pore-waters for benthic organisms. The ichnological assemblages of shallow marine systems are typically optimal for marine organisms, and as a consequence ichnological assemblages are commonly diverse. The major paleoenvironmental controls on trace fossil abundance and diversity in shallow marine

systems are considered to be hydrodynamic energy/sedimentation rate, salinity, and to a lesser extent substrate consistency.

Fluctuations in hydrodynamic energy, salinity, and sedimentation rate exist in shallow marine systems, particularly in proximity to fluvial systems in the shore-parallel direction. Fluctuations in energy, salinity and sedimentation rate exist along strike, and dip in ancient depositional environments, with variability diminishing seaward of the distributary mouth to the outer shelf. The benthic ecosystems of the offshore shelf are typically independent of hydrodynamically related stress (e.g. salinity wedge and wave action). The most common controls on the distribution of trace fossils and bioturbation intensity in distal settings are larval settling and inter-species interactions (e.g. predation and competition). Bioturbation intensity and ichnodiversity typically increase systematically in an offshore direction, from the shoreface to the shelf.

In nearshore settings, the combination of fluvial, tidal and wave processes produces distinct environments for benthic organisms. The resultant sedimentary facies therefore have distinctive ichnological signatures (see Chapter 3). No single trace fossil is diagnostic of a shallow marine facies, rather the trace fossil assemblage in an ichnofabric or ichnofacies, when considered in their sedimentological context, may be used in paleoenvironmental interpretation.

1.4 Ichnological Analysis

Ichnological analysis of sedimentary rocks is a powerful tool in facies characterization. Infaunal and epifaunal trace-producing organisms adjust their

behaviour to suit changes in environmental parameters (Figures 1.1 and 1.2). Sedimentological and ichnological data are combined and assessed using the concepts of ichnofabric analysis and application of the ichnofacies paradigm (following McIlroy, 2008).

1.4.1 Ichnofabric Analysis

Ichnofabric is defined as "all aspects of the texture and internal structure of sediment that result from bioturbation at all scales" (Bromley, 1990; p. 269). Ichnofabric analysis is a description of the ichnology, diversity, bioturbation level and colonization order of bioturbated beds (see review in Taylor *et al.*, 2003; McIlroy, 2004a for detailed methodology). Bioturbated sedimentary fabrics are studied on a bed-by-bed basis, and involve quantification of bioturbation intensity, documentation of diversity and cross-cutting relationships (Figure 1.2 and Table 1.1).

The ichnofabric analysis approach uses the ichnofabric constituent diagram (ICD, Figure 1.3) and the Bioturbation Index (BI, Table 1.1) to provide a normalised visual means for describing and comparing ichnofabrics in sedimentary rocks (Taylor and Goldring, 1993). The ichnofabric analysis method is used to: identify key stratigraphic surfaces (Taylor and Gawthorpe, 1993; Goldring, 1995; Droser *et al.*, 2002); and formulate depositional models (Droser and Bottjer, 1989; Bottjer and Droser, 1991; Ekdale and Bromley, 1991; Pollard *et al.*, 1993; Martin and Pollard, 1996; Gowland, 1996; McIlroy, 2004a, b), and create fully integrated reservoir characterizations (Bockelie, 1991; Taylor and Gawthorpe, 1993; McIlroy, 2007; Tonkin *et al.*, 2010).

Grade	% Bioturbated	Classification
0	0	No bioturbation
1	1-4%	Sparse bioturbation: bedding distinct, few discrete traces and/or escape structures
2	5-30%	Low bioturbation: bedding distinct, low trace density, escape structures often common
3	31-60%	Moderate bioturbation: bedding boundaries sharp, traces discrete, overlap rare
4	61-90%	High bioturbation: bedding boundaries indistinct, high trace density with overlap common
5	91-99%	Intense bioturbation: bedding completely disturbed, limited reworking, later burrows discrete
6	100%	Complete bioturbation: sediment reworking due to repeated overprinting

Table 1.1. The Bioturbation Index (redrawn from Taylor and Goldring, 1993) indicates the percentage of bioturbation within the substrate. Grade or degree of bioturbation ranges from 0 to 6 (also expressed as a percentage); a zero grade represents no bioturbation while grade six represents complete bioturbation.

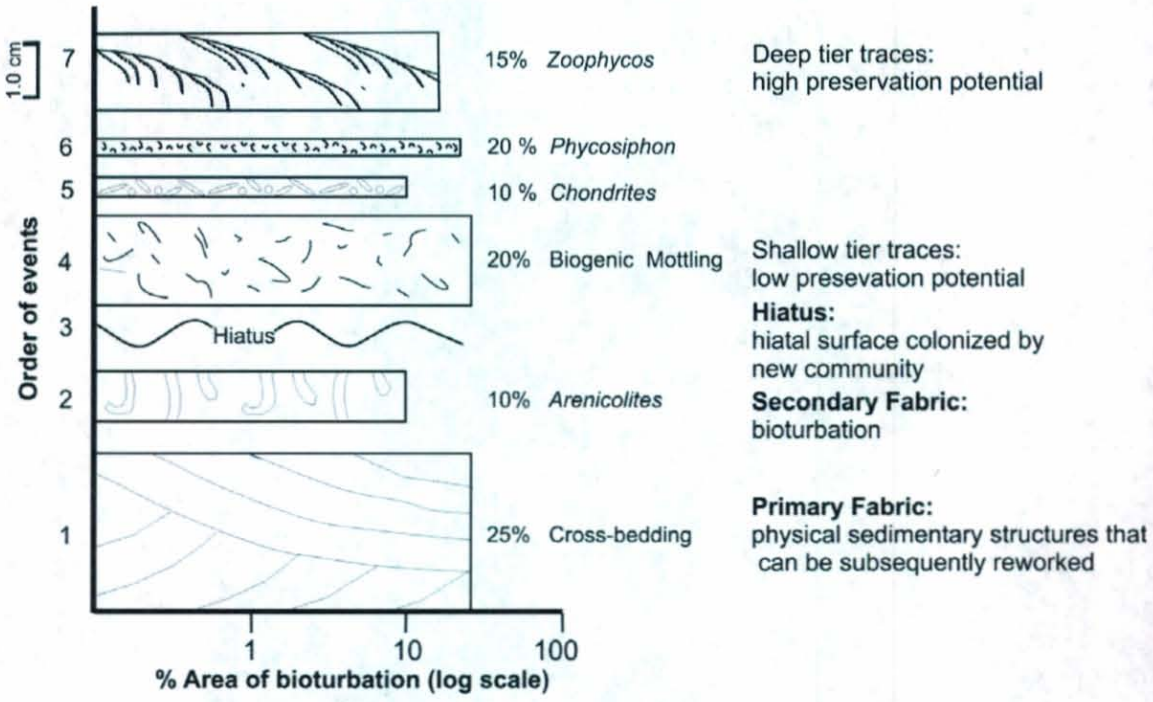


Figure 1.3. Ichnofabric Constituent Diagram (ICD; after Taylor and Goldring, 1993). The ICD is a visual representation of one or more ichnofabrics. The diagram neatly illustrates ichnotaxan identification, burrow size and extent (% area of bioturbation), colonization order and tiering, sedimentary structures, and key stratal surfaces. The ICD figure is reversed from the original so that it is consistent with the principle of superposition (following McIlroy, 2004a).

Ichnological analysis when integrated with detailed sedimentological studies is readily applicable to siliciclastic sedimentation, and highlights ichnological response to changes in environmental conditions (Taylor and Goldring, 1993; McIlroy, 2004c, 2008; Figure 1.2). This method allows direct comparison of different ichnofabrics from different geographic or stratigraphic successions. The focus on cross-cutting relationships can provide insights into community development and tiering to determine ichnocoenoses (Figure 1.2).

1.4.1.1 Bioturbation Intensity

Intensity of bioturbation and ichnological diversity in shallow marine settings are useful first-order tools in recognition of facies, facies association and the dominant process that influenced the assemblage of trace fossils that the rocks host. Bioturbation intensity, known as the bioturbation index (BI, Table 1.1) is based on the amount of reworking with respect to the original sedimentary fabric (Taylor and Goldring, 1993). The bioturbation index ranges from BI 0 which represents an unbioturbated lithology and extends up to BI 6, 100% which is complete biological reworking of the primary sedimentary fabric (Table 1.1). This index is different from the ichnofabric indices (II) of Droser and Bottjer (1986), as they do not allow recognition of the relationship of traces to background sedimentation or event stratigraphy. Highly bioturbated successions are commonly well-oxygenated, and have abundant food supply, providing optimal conditions for creation of burrows, tracks and trails on the ancient seafloor. Such intensely bioturbated facies can occur in a range of shallow marine facies, with the pre-requisite being a rate of bioturbation which is greater than the rate of sedimentation.

1.4.1.2 Recording of ichnotaxa

In this thesis, ichnotaxonomic identification was typically made at the ichnogeneric rather than ichnospecific level. In most cases ichnospecies-level ichnotaxobases are not evident in ichnofabric studies from cut slabs. Parameters such as burrow size, burrow-fill, morphology, cross-cutting relationships, tier level, abundance, and depth below event bed are documented for each identified ichnofossil in the ichnofabric studies presented herein (see Chapter 3). Documentation of other ichnological textures such as burrow mottling (Savrda and Bottjer, 1989; Gingras *et al.*, 2004), and cryptobioturbation (Pemberton *et al.*, 2008) are equally important for facies modelling, and reservoir characterization.

1.4.1.3 Ichnodiversity

Preserved ichnodiversity is influenced by: 1) taphonomy (e.g. loss of preservation through physical and diagenetic processes); 2) sediment textural and mineralogical maturity; 3) colonization history; 4) intensity of bioturbation (e.g. overprinting or rapid deposition); and 5) the taxonomic philosophy of the investigator (e.g. sedimentologist versus specialist ichnologist). Diversity of a trace fossil assemblage should not be directly linked to species diversity or abundance on the ancient seafloor, because organisms have the ability to create multiple burrow morphologies (behavioural plasticity), and to create extensive burrow networks (e.g. *Thalassinoides*) that may obscure or enhance diversity. The presence of monotaxic

assemblages in a stratigraphic succession is usually taken to be indicative of a "stress" in paleoenvironments of high energy, high rates of sedimentation and lowered salinity.

There is a strong preservational bias towards mid- to deep- tier trace fossils (the shallow mixed layer for example may be removed by erosion or overprinted during sediment accumulation by the transition layer, Figures 1.2 and 1.3). Ichnodiversity cannot be used as a direct indicator of biological species diversity, but can be used (with care) to document facies change.

1.4.1.4 Burrow size

The maximum burrow diameter of each ichnotaxon was measured in all case studies presented herein. Variations in burrow size can indicate organism response to change in environmental conditions including oxygenation and salinity (Ekdale and Bromley, 1991; Savrda and Bottjer, 1991; MacEachern *et al.*, 2007a; Gingras *et al.*, 2011).

1.4.1.5 Burrow fill

Recognition of the lithology and internal structure of burrow fill is important when examining depositional history of a bed or surface, in particular the relationship of the causative open burrow to a particular stratigraphic horizon. The taphonomic expressions of trace fossils and the relationship of the burrow fill to the host sediment, (subtle lithological contrast or distinct lithological contrast) can be used to recognize a key stratigraphic surface, and accompanying depositional history (see Chapter 4).

1.4.1.6 Cross-cutting relationships

The basic geological principle of cross-cutting relationships applies to trace fossils. In ichnofabrics these relationships represent the colonization order of ichnotaxa (Figure 1.3). In addition, sedimentation rates and recognition of condensed beds can be determined through identifying cross-cutting relationships between different ichnotaxa and overprinting of ichnofabrics (Taylor *et al.*, 2003; Figures 1.2 and 1.3).

1.4.1.7 Ichnofabric Constituent Diagram (ICD)

The ichnofabric constituent diagram (ICD, Figure 1.3) is a visual representation of one or more ichnofabrics. The diagram displays components of the ichnofabric including, ichnotaxon identification, bioturbation intensity (BI), burrow size and abundance, colonisation order and tiering, sedimentary structures, and key stratigraphic surfaces. Together these features of the ICD graphically represent the characteristics of an ichnofabric and its development through time in response to changing paleoenvironmental conditions (Taylor and Goldring, 1993; McIlroy, 2004a). This diagram provides detailed information for high-resolution paleoenvironmental and paleoecological reconstructions.

1.4.2 Ichnofacies

Bioturbated rocks can also be categorized using Seilacherian ichnofacies (see MacEachern *et al.*, 2007c for detailed methodology). The archetypal ichnofacies concept (Seilacher, 1964, 1967a, b) is widely used to describe trace fossil associations

and facies successions in terrestrial and marine environments (Figure 1.4). Originally, ichnofacies were considered to be bathymetrically controlled (e.g. Seilacher, 1964). The current definition of an ichnofacies is a recurring ichnological assemblage that has paleoenvironmental implications (Bromley and Asgaard, 1991). Ichnofacies are not restricted to specified salinity or bathymetric conditions and can occur in a range of marine and non-marine environments (Frey *et al.*, 1990; Bromley and Asgaard, 1991). This broadening of ichnofacies concept, defines ichnofacies as being paleoenvironmentally controlled, rather than a simple paleobathymetric proxy (Frey *et al.*, 1990).

Each ichnofacies is named after a typical trace fossil, but the particular trace need not appear in the ichnological assemblage (Figure 1.4). In this study, ichnofacies were identified for each comparable ichnofabric (Chapters 2 and 3). Three archetypal ichnofacies have been identified from siliciclastic shallow marine settings; *Skolithos*, *Cruziana*, and *Glossifungites*. General definitions of these three ichnofacies are summarised from Frey *et al.* (1990); Bromley and Asgaard (1991); and Bromley (1996):

1) *Skolithos* ichnofacies – a suite of softground trace fossils, generally with low diversity, typically associated with high energy conditions in clean, well sorted shifting substrates.

2) *Cruziana* ichnofacies – characterised by a high preservation potential of shallow to mid tier traces in relatively low energy conditions. Ichnodiversity is high and benthic communities consist of a mixture of deposit feeders and suspension feeders.

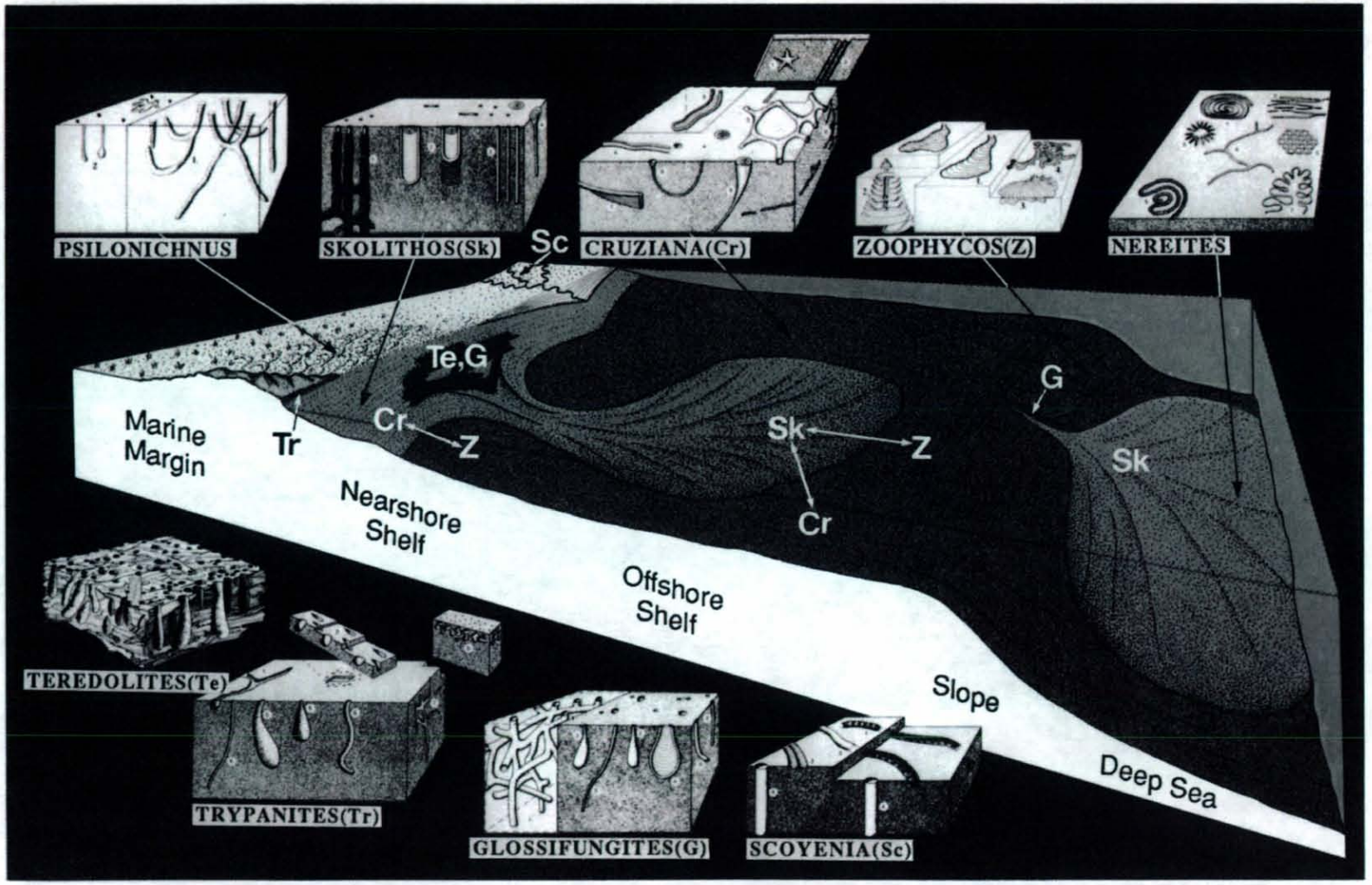


Figure 1.4. Distribution of archetypal ichnofacies in the marine realm (taken from Frey *et al.*, 1990).

3) *Glossifungites* ichnofacies - a suite of firmground burrows and/or borings, generally with low diversity. It occurs locally, intercalated with softground horizons, or can be exhumed by localised erosion and/or event deposition.

Ichnological analysis of sedimentary rocks is a powerful tool in facies analysis and reservoir characterization (Gingras *et al.*, 1999; Pemberton *et al.*, 2001; Buatois *et al.*, 2002; McIlroy, 2004, 2008; Pemberton and Gingras, 2005; Gingras *et al.*, 2007, 2010). The objective of ichnofacies and ichnofabric analysts is the same, to determine ancient paleoenvironments. Both methodologies do this successfully and generally come to comparable conclusions (McIlroy, 2008). A neutral ichnological analysis approach has been proposed, and abandonment of the conflicting terms of ichnofacies and ichnofabric has been suggested (McIlroy, 2008).

1.5 Shallow Marine Facies Models

Coastlines are dynamic settings where fluvial and marine processes interact to produce a diverse array of depositional environments (see reviews in Reading and Collinson, 1996; Posamentier and Walker, 2006). Fluvial, tidal and wave processes produce distinctive coastal morphologies, as well as having diagnostic lateral and stratigraphic facies trends (Boyd *et al.*, 1992; Figure 1.5). Combinations of these parameters are evident in the resultant sedimentology and ichnology. Sedimentological analysis is used as the primary tool to define shallow marine settings and their facies. Ichnological variability in response to the same hydrodynamic parameters provides an excellent additional tool in recognition of marginal marine to shelfal facies. Integration of sedimentology and ichnology enables us to construct

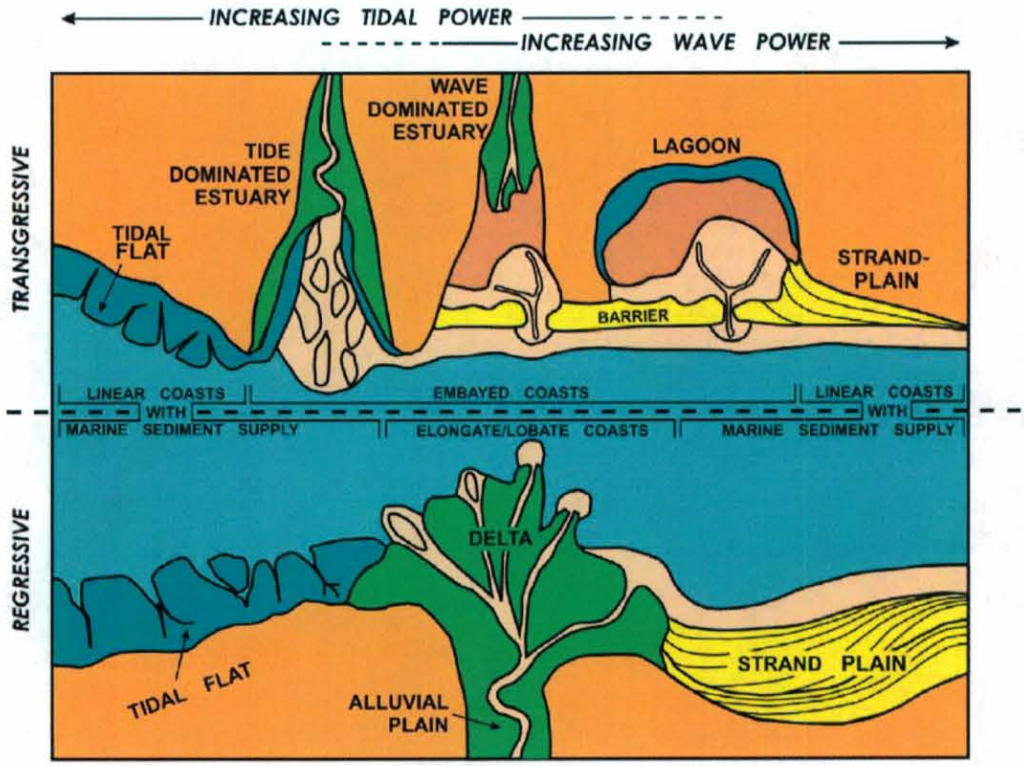


Figure 1.5. Coastal classification of major clastic coastal depositional environments. Based on shoreline progradation or transgression, and power of waves, tidal currents and river currents (from Boyd, 2010; after Boyd *et al.*, 1992).

more comprehensive reservoir, facies, and paleoenvironmental models (Pemberton *et al.*, 2001; McIlroy, 2004a, b, 2008; MacEachern *et al.*, 2010).

Deltaic coastlines are sites of net sediment deposition where a river enters a body of water (Galloway, 1975). Deltas are progradational features that form discrete shoreline protuberances where the alluvial-fluvial system delivers sediment more rapidly than can be redistributed away from the distributary mouth by waves and tides (Orton and Reading, 1993). Estuaries are associated with net shoreline transgression with high—usually eustatically driven—rates of accommodation space generation relative to rates of sediment supply (Boyd *et al.*, 1992). Non-deltaic coastlines derive their sediment from the adjacent coastline and shelf, and are not fed directly by a river sediment supply. These coastal areas include beaches, strand-plains, barrier-island systems, lagoons, estuaries and tidal flats (James and Dalrymple, 2010).

Deltaic and non-deltaic coastlines and the associated depositional systems are part of a continuum linked to shoreline regression and transgression, and are influenced by wave, tidal, and fluvial currents (Figure 1.5; Boyd *et al.*, 1992). Characterization of ancient deltas is somewhat challenging. The deltaic morphology (e.g., elongate versus lobate; Bhattacharya, 2006) is difficult to characterize in ancient deposits. For example, ancient wave-dominated river deltas develop shoreface facies and may be difficult to distinguish from non-deltaic shorelines, unless the large-scale spatial context is well delineated by seismic data, good outcrop exposures or closely spaced, reliably correlated core or well-log data (Hampson and Howell, 2005).

1.6 Facies Analysis

A facies is a body of rock with specific lithological, physical and biogenic characteristics (see reviews in Walker, 1992; Reading, 1996; James and Dalrymple, 2010). The body of rock termed a facies may be a single bed or a group of beds. The facies name may be purely descriptive (e.g. bioturbated sandy mudstone), or interpretive (e.g. shoreface facies). When facies are used in a descriptive manner it allows for objective and transparent environmental interpretations. Groups of facies that are genetically or environmentally linked to one another are termed facies associations, and are deposited under specific environmental conditions (Collinson, 1996). Facies and facies associations are distilled into a facies model that characterizes the depositional system; this model is drawn from both ancient and modern examples (Walker, 1992). An integral principle in construction of a facies model is 'Walther's Law' or the 'Law of Correlation of Facies' (Middleton, 1973). Walther's Law states that a vertical succession of conformable facies accumulated in laterally adjacent depositional environments. In this research project the facies analysis approach is used to interpret depositional environments (Figure 1.5). Ichnological analysis can be incorporated into a facies model as an additional building block in the interpretation of the depositional environment (McIlroy, 2008).

1.7 Laboratory Analyses

Sedimentary rock specimens were sampled from each outcrop locality for each case study. The aim of sample analysis was to determine: 1) petrology (slab sample and thin section analysis); and 2) petrophysical properties (porosity and permeability). Hand specimens were described in detail including color, texture, composition, sedimentary structures, and trace fossil and fossil content. Slab faces of samples were sliced for preparation of large thin slice (Figure 1.6), and thin section analysis. The remainder of the samples underwent spot permeability measurement on the slab surface (using a probe permeameter, Figure 1.7).

1.7.1 Large Thin Slicing

The technique of large thin slicing is used to study the sedimentary and biogenic fabrics in sandstone and mudstone lithologies in transmitted light (Garton and McIlroy, 2006). A large thin slice is cut from the hand specimen using a rock saw fitted with a travelling vice. The cut slice of 2-3 mm is then mounted with epoxy or wax onto a large glass slide (28 x 20 cm). The mounted slice is further reduced in thickness by lapping on a rotating lapidary wheel until translucent (Figure 1.6). The thickness required varies between samples from between 0.3 to 1.0 mm, dependent on the grain size of the sample. The large thin slices were photographed with a mounted camera in transmitted light using a 500 W halogen light with a parabolic reflector. Large thin slicing is particularly useful where weathering or diagenetic processes (e.g. cement) may mask sedimentary, or biogenic features, or in very fine grained facies (Garton and McIlroy, 2006). The resultant images when viewed in transmitted light,

Figure 1.6. Large thin slicing technique (see Garton and McIlroy, 2006). Slice cut from core slab, then adhered to a glass slide. When viewed in transmitted light samples display sedimentary structures, and detailed ichnology not otherwise visible.

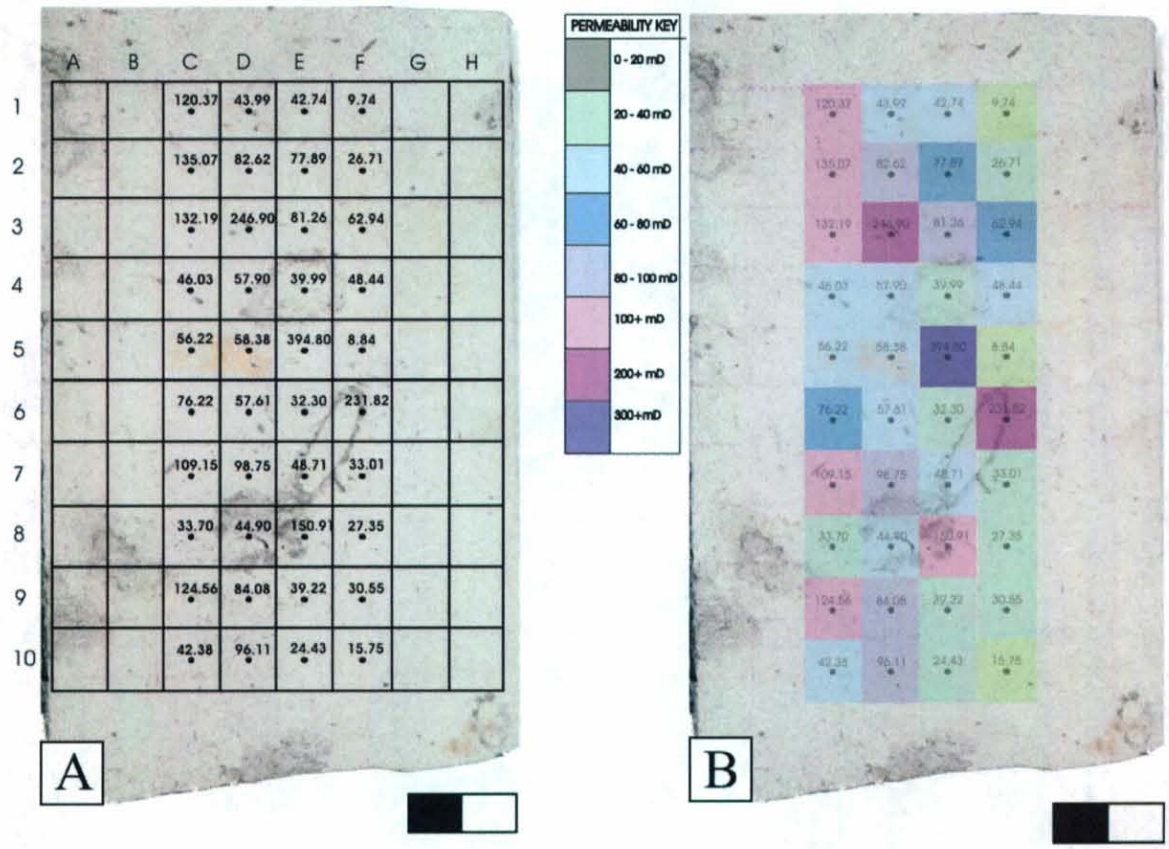


Figure 1.7. Spot-permeability measurements overlain on core slab face. Grid squares at 1cm spacings with warm colors (e.g. D3 and F8) display relatively higher permeability than cool colored grid squares (e.g. F1 and C4).

show sedimentary structures and detailed ichnology that is not otherwise visible in polished hand specimen or field samples (Figure 1.6).

1.7.2 Thin Section Analysis

Thin sections (4.5 x 2.7 cm) were cut from each sample. Detailed petrographical analysis of each thin section was undertaken, including description of texture, grains, matrix, compaction, cementation, porosity, classification and photography. Petrography provides micro-fabric detail which aids in accurate sedimentological classification, mineralogical composition, and enables identification of mineralogical burrow-grain relationships.

Thin sections were impregnated with blue epoxy resin, in order to highlight pore spaces when viewed under the microscope. Visual estimates of grain sorting were measured using comparison charts (Jerram, 2001). Digital image analysis software (Simple PCI®) is used to calculate the relative proportions of 'blue' pore space in a given area of interest, and this 2D visual measurement is taken as a proxy for the corresponding porosity. Porosity is a measure of the proportion of void spaces in a material, and is commonly quantified as a percentage. Porosity was determined in bioturbated samples to: 1) assess the influence of biogenic reworking on porosity; 2) document variability in porosity relative to bioturbation intensity; and to be able to directly relate bioturbation to reservoir quality.

1.7.3 Probe Permeametry

A probe-permeameter (TEMCO Inc. MP-401) was used to measure permeability (k) in the collected samples. Permeability is the measure of the ability a material to transmit fluids (expressed as the millidarcy (mD)). The equipment measures the flow rate and injection pressure of nitrogen gas into a rock. The probe-permeameter injects compressed nitrogen gas into the rock using a probe-tip of 3.18-6.35 mm inner-outer diameter, and measures the flow rate and injection pressure in a rock volume of approximately $1cm^3$. In each of the slab samples, a 1cm-grid was drawn on the surface, and spot horizontal permeability measurements were taken in the centre of each square (cf. Dreyer *et al.*, 1990; Figure 1.7).

Data acquisition and analysis was calculated using the SmartPermTM software to measure the effective permeability. In each slab samples a 4cm by 10cm grid was drawn on the slab face. The spacing between columns and rows is 1cm. Permeability in millidarcies (mD) was calculated using the appropriate form of Darcy's equation modified by the half-space solution of a geometrical factor G_0 as a function of probe-tip seal thickness (Goggin *et al.*, 1988). Four measurements were taken of the same point on the grid to obtain an average and at least 40 grid point measurements were obtained from each sample (Figure 1.7). The permeability data was overlain and compared to sedimentological (large thin slice image and thin section) and ichnological data (see Chapter 2).

1.8 Reservoir quality prediction in bioturbated successions

Effective production of petroleum from bioturbated reservoirs requires reliable prediction of facies-related reservoir properties. In such bioturbated settings, facies analysis and reservoir characterization are essentially ichnological analysis (McIlroy, 2008). Bioturbation can redistribute grains and cause sorting or mixing (see Chapter 2), this physical modification of the primary sedimentary fabric effects porosity and permeability in reservoir facies. Some ichnotaxa produce zones of enriched mud/organic matter (e.g., pellet burrow linings) or mud-reduced zones by removing the inter-particle clay-grade between sand grains (e.g., burrow matrix/halo; Tonkin *et al.*, 2010; Bednarz and McIlroy, 2009; see discussion in Chapter 2). Bioturbation of reservoir facies can either enhance or reduce porosity and permeability, and is important when calculating reserves (Pemberton and Gingras, 2005, Meyer and Krause, 2006; Tonkin *et al.*, 2010).

1.8.1 Porosity and Permeability

The majority of studies discussing the relationship of bioturbation to porosity and permeability in carbonate and siliciclastic reservoirs have focused on burrow-enhanced porosity/permeability trends (Gingras *et al.*, 1999, 2002, 2004; Smith *et al.*, 2003; Pemberton and Gingras 2005; Spila *et al.*, 2007; Florea *et al.*, 2009; Cunningham *et al.*, 2009). The literature on the effects of bioturbation on petroleum reservoirs is biased towards permeability-enhancing trace fossils of *Ophiomorpha*, *Phycosiphon*, *Macaronichnus*, *Thalassinoides*,*Zo ophycos*, and *Glossifungites* surfaces (Gingras *et al.*, 1999, 2002, 2004, 2007, 2010; Cunningham *et al.*, 2009; Knaust,

2009; Gordon *et al.*, 2010; Tonkin *et al.*, 2010; Chapter 2 herein). This thesis documents the effect of bioturbation on petrophysical properties and focuses on the more common but subtle heterogeneities in shallow marine sandstone reservoirs (Chapter 2).

1.9 Spatial variability of trace fossils

Lateral variability is of relevance to understanding trends in paleoecology through time, flow in porous media, and determines the productivity of some bioturbated petroleum reservoirs (Pemberton and Gingras, 2005). Knowledge of the lateral variability of bioturbation and application of a more quantitative ichnological methodology is required to make reliable predictions of reservoir properties (see discussion in Chapter 3). Most studies of bioturbation have been aimed at understanding changes in vertical stratigraphic profiles (Pemberton and Gingras, 2005; Gingras *et al.*, 2007). Lateral variability is significantly understudied but of relevance to understanding flow in porous media, and can determine the productivity of some bioturbated petroleum reservoirs.

Studies in lateral variability of trace fossils are beginning to give an impression of *in situ* spatial variability of ichnofabrics (McIlroy, 2007), with the additional insight into variations in sedimentation rate, hydrodynamic energy (erosive currents), substrate consistency, length of colonization window, community structure and succession (tiering and cross-cutting relationships). Ichnofabric analyses along a highly bioturbated lateral profile (55 m), demonstrate there is considerable along-strike ecological patchiness in offshore shelf settings, given the expected

hydrodynamic homogeneity at this scale (McIlroy, 2007). This thesis uses onshore to offshore case studies to create a first order understanding of likely lateral ichnological variability in a number of depositional environments that may be incorporated into reservoir to basin scale models of shallow marine hydrocarbon reservoirs and paleoecological models (Chapter 3).

1.10 Key stratigraphic surfaces and bioturbation

Key stratigraphic surfaces (erosion, non-deposition or condensation) in bioturbated successions are clearly identifiable where there is a distinct facies change, variation in bioturbation intensity, trace fossil cross-cutting relationships, and lithological contrast in burrow fill relative to the host sediment. Trace fossils observed at key stratigraphic surfaces include *Thalassinoides*, *Planolites*, and *Ophiomorpha* (Pemberton *et al.*, 1992; Taylor and Gawthorpe, 1993; Bromley, 1996; Gowland, 1996; Gingras *et al.*, 2002, 2008; Taylor *et al.*, 2003; McIlroy, 2004b; MacEachern and Gingras, 2008; see Chapter 4). These surfaces can have allostratigraphic, autocyclic, or ecologic significance and can be fundamental in identification of sequence stratigraphic surfaces (Einsele *et al.*, 1991; Catuneanu *et al.*, 2009).

The fill of *Thalassinoides*, *Planolites*, and *Ophiomorpha* are commonly found to correspond to that of the lithology of the overlying colonization surface. This is generally taken to indicate that the burrow was kept open with burrower/borer-induced water currents (Sheehan and Schiefelbein, 1984), or that the burrow was constructed in a firm substrate not prone to collapse. Modern thalassinid shrimps

construct burrows that resemble *Ophiomorpha* and *Thalassinoides* with vertical shafts connected to horizontal to oblique galleries at depths of up to 1 metre below the sediment-water interface (Pryor, 1975; Sheehan and Schiefelbein, 1984; Swinbanks and Luternauer, 1987; Phillips *et al.*, 2011). Analogous fossil burrow systems thus have the potential to produce enhanced permeability fabrics within sedimentary successions (e.g., Cunningham *et al.*, 2009; Pemberton and Gingras, 2005; Tonkin *et al.*, 2010). Sand-filled *Thalassinoides* may potentially produce vertical and horizontal macropore networks with the potential to act as flow conduits in hydrocarbon reservoirs (Gingras *et al.*, 1999; Tonkin *et al.*, 2010).

Taphonomic expressions of bioturbated stratal surfaces and the relationship to the enclosing sediment allows recognition of bioturbated stratigraphic surfaces and their relationship to the enclosing sediment allows assessment of the sequence stratigraphic significance, depositional history, and paleoenvironmental change associated with that surface. This thesis uses *Thalassinoides* as a tool in identification of key stratigraphic surfaces because of the: 1) abundance of *Thalassinoides* in the geological record; 2) distribution of *Thalassinoides* in a wide range of depositional and geographical environments; 3) ease of identification in core and outcrop; and 4) ability of the *Thalassinoides* trace maker to colonize a variety of substrate types including softgrounds and firmgrounds (Chapter 4).

1.11 Thesis Structure

A variety of case studies of onshore to offshore shallow marine facies are used in this thesis, including: 1) Quaternary fan deltaic succession, Conway Flat, New

Zealand; 2) Early Cretaceous shoreface succession, offshore Newfoundland, Canada; 3) Late Cretaceous shoreface succession, Book Cliffs, Utah, USA; 4) Middle Jurassic tide-influenced deltaic succession, Neuquén Basin, Argentina; and 5) Neogene shelf succession, East Cape, Raukumara Basin, New Zealand. This thesis is submitted in manuscript style. The following four chapters are summarized below.

1.11.1

Chapter 2: Bioturbation influence on reservoir quality: A case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, Offshore Newfoundland, Canada.

This manuscript investigates the role bioturbation has in controlling the petrophysical properties of sandstone reservoir intervals. Quantitative permeability and porosity is presented while ichnotaxa are discussed and categorized with respect to their sediment modification behaviour, and enhancement or reduction of permeability. The burrowing activity of marine organisms is grouped into five categories with predictable effects on porosity and permeability.

1.11.2

Chapter 3: Lateral trends in the ichnological variability of shallow marine successions

This manuscript discusses the lateral variability of ichnological and sedimentological properties of three along-strike horizontal transects. Three datasets

are analyzed: 1) a Quaternary proximal fan delta succession (New Zealand); 2) a Cretaceous shoreface succession (Utah); and 3) a Miocene offshore shelf succession (New Zealand). These case studies are used to produce a first order understanding of likely lateral ichnological variability in a number of depositional environments. Lateral trends in ichnological variability may be incorporated into reservoir- to basin-scale models of shallow marine hydrocarbon reservoirs and paleoecological models.

1.11.3

Chapter 4: Bioturbated key stratigraphic surfaces and their autocyclic and allocyclic implications

This manuscript examines the complexity and significance of *Thalassinoides*-bearing surfaces (erosion, non-deposition or condensation). Autocyclic and allocyclic interpretations are debated using examples from ancient shallow marine facies.

1.11.4

Chapter 5: Bioturbation as a tool in reservoir characterization

A summary chapter of how bioturbation can be used as tool to predict reservoir quality in shallow marine siliciclastic successions. A new, non-taxonomic bioturbation classification is proposed, that directly reflects the physical modifications trace-makers produce in siliciclastic facies.

References

Ainsworth, R.B., B.K. Vakarelov, and R.A. Nanson, 2011, Dynamic spatial and temporal prediction of changes in depositional processes on clastic shorelines: Toward improved subsurface uncertainty reduction and management: AAPG Bulletin, v. 95, p. 267-297.

Ausich, W. I., and D. J. Bottjer. 1982, Tiering in suspension feeding communities on soft substrata throughout the Phanerozoic: Science, v. 216, p. 173-174.

Bednarz, M., and D. McIlroy, 2009, Three-dimensional reconstruction of "phycosiphoniform" burrows: implications for identification of trace fossils in core: Palaeontologica Electronica, v. 12, 15p; http://palaeo-electronica.org/2009_3/195/index.html.

Bentley, S. J., and C.A. Nittrouer, 2003, Emplacement, modification, and preservation of event strata on a flood-dominated continental shelf: Eel shelf, Northern California: Continental Shelf Research, v. 23, p. 1465–1493.

Bentley, S.J., and A. Sheremet, 2003, New model for the emplacement, bioturbation, and preservation of fine-scaled sedimentary strata: Geology, v. 31, p. 725-728.

Berger, W. H., A.A. Ekdale and P.P. Bryant, 1979, Selective preservation of burrows in deep-sea carbonates: Marine Geology, v. 32 , p. 205-230.

Bertling, M., S.J. Braddy, R.G. Bromley, G.R. Demathieu, J. Genise, R. Mikulas, J.K. Nielsen, A.K. Rindsberg, M. Schlirf, and A. Uchman, 2006, Names for trace fossils: a uniform approach: Lethaia, v. 39, p. 265-286.

Bhattacharya, J.P., 2006, Deltas, *in* H.W. Posamentier, and R.G. Walker, eds., Facies Models Revisited: SEPM Special Publication 84, p. 237–292.

Bhattacharya, J.P. and J.A. MacEachern, 2009, Hyperpycnal rivers and prodeltaic shelves in the Cretaceous Seaway of North America: Journal of Sedimentary Research, v. 79, p.184-209.

Bockelie, J.F., 1991, Ichnofabric mapping and interpretation of Jurassic reservoir rocks of the Norwegian North Sea: Palaios, v. 6, p. 206-215.

Bottjer, D.J. and M.L. Droser, 1991, Ichnofabric and basin analysis, Palaios, v. 6, p. 199-205.

Boyd, R., 2010, Transgressive wave-dominated coasts, *in* N.P James, and R.W. Dalrymple, eds., Facies Models 4: St John's, Geological Association of Canada, p. 265-294.

Boyd, R., R.W. Dalrymple, and B.A. Zaitlin, 1992, Classification of coastal sedimentary environments: Sedimentary Geology, v. 80, p. 139–150.

Boyd, R., R.W. Dalrymple, and B.A. Zaitlin, 2006, Estuarine and incised-valley facies models, *in* H.W. Posamentier and R.G. Walker, eds., Facies models revisited: SEPM Special Publication 84, p. 171-235.

Brandsæter, I., D. McIlroy, O. Lia, P. Ringrose and A. Næss, 2005, Reservoir modelling and simulation of Lajas Formation outcrops (Argentina) to constrain tidal reservoirs of the Halten Terrace (Norway): Petroleum Geoscience, v. 11, p. 37-46.

Brettle, M.J., D. McIlroy, T. Elliot, S.J. Davies and C.N. Waters, 2002, Identifying cryptic tidal influences within deltaic successions: an example from the Marsdenian (Namurian) interval of the Pennine Basin, UK: Journal of the Geological Society, London, v. 159, p. 379–391.

Bromley, R.G., 1990, Trace fossils: biology and taphonomy: London, Unwin Hyman, 280 pp.

Bromley, R.G., 1996. Trace fossils: biology, taphonomy and applications: London, Chapman and Hall, 361 pp.

Bromley, R.G., and A.A. Ekdale, 1984, *Chondrites*: a trace fossil indicator of anoxia in sediments: Science, v. 224, p. 872-874.

Bromley, R.G. and U. Asgaard, 1991, Ichnofacies; a mixture of taphofacies and biofacies: Lethaia, v. 24, p. 153-163.

Buatois, L.A., M.G. Mangano, C.G. Maples, W.P. Lanier, 1997, The paradox of nonmarine ichnofaunas in tidal rhythmites: integrating sedimentologic and ichnologic data from the Late Carboniferous of Eastern Kansas, USA: Palaios, v. 12, p. 467-481.

Buatois, L.A., M.K., Gingras, J.A. MacEachern, M.G. Mangano, J.P. Zonneveld, S.G. Pemberton, R.G. Netto, and A. Martin, 2005, Colonization of brackish-water systems through time: evidence from the trace-fossil record: Palaios, v. 20, p. 321–347.

Buatois, L.A., M.G. Mángano, A. Alissa and T.R. Carr, 2002, Sequence stratigraphic and sedimentologic significance of biogenic structures from a late Paleozoic marginal- to open-marine reservoir, Morrow Sandstone, subsurface of southwest Kansas, USA: Sedimentary Geology, v. 152, p. 99-132.

Buatois, L.A., N. Santiago, K. Parra, R. Steel, 2008, Animal–substrate interactions in an Early Miocene wave-dominated tropical delta: delineating environmental stresses and depositional dynamics (Tácata Field, Eastern Venezuela): Journal of Sedimentary Research, v. 78, p. 458–479.

Cannon, S.J.C., and S. Gowland, 1996, Facies controls on reservoir quality in the Late Jurassic Fulmar Formation, Quadrant 21, UKCS, *in* A. Hurst, H.D. Johnson, S. D. Burley, A.C. Canham, and D.S. Mackertich, eds., Geology of the Humber Group: Central Graben and Moray Firth, UKCS: Geological Society (London) Special Publication 114, p. 215-233.

Catuneanu, O., V. Abreu, J.P. Bhattacharya, M.D. Blum, R.W. Dalrymple, P.G. Eriksson, C.R. Fielding, W.L. Fisher, W.E. Galloway, M.R. Gibling, K.A. Giles, J.M. Holbrook, R. Jordan, C.G.St.C. Kendall, B. Macurda, O.J. Martinsen, A.D. Miall, J.E. Neal, D. Nummedal, L. Pomar, H.W. Posamentier, B.R. Pratt, J.F. Sarg, K.W. Shanley, R.J. Steel, 2009, Towards the standardization of sequence stratigraphy: Earth-Science Reviews, v. 92, p. 1-33.

Collinson, J.D., 1996, Alluvial sediments, *in* H.G. Reading, ed., Sedimentary Environments and Facies: Oxford, Blackwell Science, p. 37–82.

Crerar, E.E., and R.W.C. Arnott, 2007, Facies distribution and stratigraphic architecture of the Lower Cretaceous McMurray Formation, Lewis Property, northeastern Alberta: Bulletin of Canadian Petroleum Geology, v. 55, p. 99-124.

Cummings, D.I., R.W.C. Arnott, and B.S. Hart, 2006, Tidal signatures in a shelf-margin delta: Geology, v. 34, p. 249-252.

Cunningham, K.J., M.C. Sukop, H. Huang, P.F. Alvarez, H.A. Curran, R.A. Renken, and J.F. Dixon, 2009, Prominence of ichnologically influenced macroporosity in the karst Biscayne Aquifer: stratiform "super-K" zones: Geological Society of America Bulletin, v. 121, p. 164-180.

Dalrymple, R.W., 2010, Tidal depositional systems, *in* N.P James, and R.W. Dalrymple, eds., Facies Models 4: St John's, Geological Association of Canada, p. 201-231.

Dalrymple, R.W., and K. Choi, 2007, Morphologic and facies trends through the fluvial-marine transition in tide-dominated depositional systems; a schematic framework for environmental and sequence stratigraphic interpretation: Earth-Science Reviews, v. 81, p. 135-174.

Dalrymple, R.W., B.A. Zaitlin, and R. Boyd, 1992, Estuarine facies models: conceptual basis and stratigraphic implications: Journal of Sedimentary Petrology, v. 62, p. 1130-1146.

Dreyer, T.; A. Scheie, and O. Walderhaug, 1990, Minipermeameter-based study of permeability trends in channel sand bodies: AAPG Bulletin, v. 74, p. 359-374.

Droser, M.L., and D.J. Bottjer, 1986, A semiquantitive field classification of ichnofabric: Journal of Sedimentary Petrology, v. 56, p. 558-559.

Droser, M.L., and D.J. Bottjer, 1989, Ichnofabric of sandstones deposited in high-energy nearshore environments; measurement and utilization: Palaios, v. 4, p. 598-604.

Droser, M.L., S. Jensen, J.G. Gehling, P.M. Myrow, and G.M. Narbonne, 2002, Lowermost Cambrian ichnofabrics from the Chapel Island Formation, Newfoundland; implications for Cambrian substrates: Palaios, v. 17, p. 3-15.

Ekdale, A.A., 1985, Paleoecology of the marine endobenthos: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 50, p. 63-81.

Ekdale, A.A., and R.G. Bromley, 1991, Analysis of composite ichnofabrics; an example in Uppermost Cretaceous chalk of Denmark: Palaios, v. 6, p. 232-249.

Ekdale, A.A., and T.R. Mason, 1988, Characteristic trace-fossil associations in oxygen-poor sedimentary environments: Geology, v. 16, p. 720-723.

Einsele, G., W. Ricken, and A. Seilacher, 1991, Cycles and events in stratigraphy: Berlin, Springer-Verlag, 955 pp.

Fielding, C.R., 2010, Planform and facies variability in asymmetric deltas: facies analysis and depositional architecture of the Turonian Ferron Sandstone in the Western Henry Mountains, south-central Utah, U.S.A. Journal of Sedimentary Research 80, p. 455–479.

Florea, L.J., K.J. Cunningham, and S.A. Altobelli, 2009, NMR imaging of fluid exchange between macropores and matrix in eogenetic karst: Ground Water, v. 47, p. 382-390.

Frey, R.W., S.G. Pemberton, and T.D.A. Saunders, 1990, Ichnofacies and bathymetry; a passive relationship: Journal of Paleontology, v. 64, p. 155-158.

Galloway, W.E., 1975, Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems, *in* M.L. Broussard, ed., Deltas, models for exploration: Houston, Houston Geological Society, p. 87–98.

Garton, M., and D. McIlroy, 2006, Large thin slicing: a new method for the study of fabrics in lithified sediments: Journal of Sedimentary Research, v. 76, p. 1252-1256.

Gingras, M.K., S.E. Dashtgard, J.A. MacEachern, and S.G. Pemberton, 2008, Biology of shallow marine ichnology: a modern perspective: Aquatic Biology, v. 2, p. 255-268.

Gingras, M.K., J.A. MacEachern, and S.G. Pemberton, 1998, A comparative analysis of the ichnology of wave- and river-dominated allomembers of the Upper Cretaceous Dunvegan Formation: Bulletin of Canadian Petroleum Geology, v. 46, p. 51-73.

Gingras, M.K., B. Macmillan, B.J. Balcom, T. Saunders, and S.G. Pemberton, 2002, Using magnetic resonance imaging and petrographic techniques to understand the textural attributes and porosity distribution in *Macaronichnus*-burrowed sandstone: Journal of Sedimentary Research, v. 72, p. 552-558.

Gingras, M.K., C.A. Mendoza, and S.G. Pemberton, 2004, Fossilized worm burrows influence the resource quality of porous media: AAPG Bulletin, v. 88, p. 875-883.

Gingras, M.K., S.G. Pemberton, C.A. Mendoza, and F. Henk, 1999, Assessing the anisotropic permeability of *Glossifungites* surfaces: Petroleum Geoscience, v. 5, p. 349-357.

Gingras, M.K., G.S. Pemberton, F. Henk, J.A. MacEachern, C.A. Mendoza, B. Rostron, R. O'Hare, and M.V. Spila, 2007, Applications of ichnology to fluid and gas production in hydrocarbon reservoirs, *in* J.A. MacEachern, K.L. Bann, M.K. Gingras, and G.S. Pemberton, eds., Applied Ichnology: SEPM Short Course Notes 52, p. 131-145.

Gingras, M.K., J.P. Zonneveld, and J.A. MacEachern, 2010, A historical perspective on applied ichnology in Western Canada: Bulletin of Canadian Petroleum Geology, v. 58, p. 97-99.

Gingras, M.K., J.A. MacEachern, and S.E. Dashtgard, 2011, Process ichnology and the elucidation of physico-chemical stress: Sedimentary Geology, v. 237, p. 115-134.

Goggin, D.J., R.L. Thrasher, and L.W. Lake, 1988, A theoretical and experimental analysis of minipermeameter response including gas slippage and high velocity flow effects: In Situ, v. 12, p. 79–116.

Goldring, R., 1995, Organisms and substrate: response and effect, *in* D. W. J. Bosence and P.A. Allison, eds., Marine Paleoenvironmental Analysis from Fossils: Geological Society (London) Special Publication 83, p. 151-180.

Gooday, A.J., C.M. Turley and J.A. Allen, 1990, Responses by benthic organisms to inputs of organic material to the ocean floor: a review: Philosophical Transactions of the Royal Society, v. 331, p. 119-138.

Gordon, J.B., S.G. Pemberton, M.K. Gingras, and K.O. Konhauser, 2010, Biogenically enhanced permeability: a petrographic analysis of *Macaronichnus segregatus* in the lower Cretaceous Bluesky Formation, Alberta, Canada: AAPG Bulletin, v. 94, p. 1779-1795.

Gowland, S., 1996, Facies characteristics and depositional models of highly bioturbated shallow marine siliciclastic strata; an example from the Fulmar Formation (Late Jurassic), UK Central Graben, *in* Hurst, A., H.D. Johnson, S.D. Burley, A.C. Canham, and D.S. Mackertich, eds., Geology of the Humber

Group; Central Graben and Moray Firth, UKCS: Geological Society (London) Special Publication 114, p. 185-214.

Gust, G., and J.T. Harrison, 1981, Biological pumps at the sediment-water interface: mechanistic evaluation of the alpheid shrimp *Alpheus mackayi* and its irrigation pattern: Marine Biology, v. 64, p. 71-78.

Hampson, G.J., and J.A. Howell, 2005, Sedimentologic and geomorphic characterization of ancient wave-dominated shorelines: examples from the Late Cretaceous Blackhawk Formation, Book Cliffs, Utah, *in* J.P. Bhattacharya, and L. Giosan, eds., River Deltas; concepts, models, and examples: SEPM Special Publication 83, p.133–154.

Häntzschel, W., 1975, Trace fossils and problematica, *in* C. Teichert, ed., Treatise on Invertebrate Paleontology, part W. Miscellanea: Boulder, Colorado, and Lawrence, Kansas, Geological Society of America and University of Kansas Press, 269 pp.

Herringshaw, L.G., O. Sherwood, and D. McIlroy, 2010, Ecosystem engineering by bioturbating polychaetes in event bed microcosms: Palaios, v. 25, p. 46-58.

Howard, J.D., 1972, Trace fossils as criteria for recognizing shorelines in stratigraphic record; Recognition of ancient sedimentary environments, *in* W.K. Hamblin, ed., Recognition of Ancient Sedimentary Environments: SEPM Special Publication 16, p. 215-225.

Howell, J.A., A. Skorstad, A. MacDonald, A. Fordham, S. Flint, B. Fjellvoll, and T. Manzocchi, 2008, Sedimentological parameterization of shallow-marine reservoirs: Petroleum Geoscience, v. 14, p. 17-34.

James, N.P., and R.W. Dalrymple, 2010, Facies Models 4: St John's, Geological Association of Canada, 586 pp.

Jerram, D.A., 2001, Visual comparators for degree of grain-size sorting in two and three-dimensions: Computers and Geoscience, v. 27, p. 485-492.

Jørgensen, B.B. and J.R. Postgate, 1982, Ecology of the bacteria of the sulfur cycle with special reference to anoxic-oxic interface environments: Philosophical Transactions of the Royal Society of London, v. 298, p. 543-561.

Knaust, D., 2009, Ichnology as a tool in carbonate reservoir characterization; a case study from the Permian-Triassic Khuff Formation in the Middle East: GeoArabia, v. 14, p. 17-38.

Konhauser, K.O., and M.K. Gingras, 2007, Linking geomicrobiology with ichnology in marine sediments: Palaios, v. 22, p. 339-342.

Labourdette, R., J. Casas, and P. Imbert, 3D Sedimentary modelleing of Miocene deltaic reservoir unit, Sincor Field, Venezuela: a new approach: Petroleum Geology, v. 31, p. 135-152.

MacEachern, J.A., and M.K. Gingras, 2008, Recognition of brackish-water trace fossil suites in the Cretaceous Western Interior Seaway of Alberta, Canada, *in* R.G. Bromley, L.A. Buatois, M.G Mangano, J.F. Genise, and R.N. Melchor, eds., Sediment –Organism interactions: A multifaceted ichnology: SEPM Special Publication 89, p. 149–194.

MacEachern, J.A., S.G. Pemberton, K. Bann, and M.K. Gingras, 2007a, Departures from the archetypal ichnofacies: effective recognition of environmental stress in the rock record, *in* J.A. MacEachern, S.G. Pemberton, M.K. Gingras, and K. Bann, eds., Applied Ichnology: SEPM Core Workshop 52, p. 65–95.

MacEachern, J.A., M.K. Gingras, K. Bann, S.G. Pemberton, and L.T. Reich, 2007b, Applications of ichnology to high-resolution genetic stratigraphic paradigms, *in*: J.A. MacEachern, S.G. Pemberton, M.K. Gingras, and K. Bann, eds., Applied Ichnology: SEPM Core Workshop 52, p. 95–131.

MacEachern, J.A., M.K. Gingras, K. Bann, and S.G. Pemberton, 2007c, The ichnofacies paradigm: high-resolution paleoenvironmental interpretation of the rock record, *in* J.A. MacEachern, S.G. Pemberton, M.K. Gingras, and K. Bann, eds., Applied Ichnology: SEPM Core Workshop 52, p. 27–65.

MacEachern, J.A., M.K. Gingras, S.G. Pemberton, and K. Bann, 2010, Ichnology and Facies Models, *in* N.P James, and R.W. Dalrymple, eds., Facies Models 4: St John's, Geological Association of Canada, p. 19-58.

Macquaker, J.H.S., S.J. Bentley, and K.M. Bohacs, 2010a, Wave-enhanced sediment-gravity flows and mud dispersal across continental shelves: reappraising sediment transport processes operating in ancient mudstone successions: Geology, v. 38, p. 947-950.

Macquaker, J.H.S., M. Keller, and S.J. Davies, 2010b, Algal blooms and "marine snow": mechanisms that enhance preservation of organic carbon in ancient fine-grained sediments: Journal of Sedimentary Research, v. 80, p. 934-942.

Mángano, M.G., and L.A. Buatois, 2004, Ichnology of Carboniferous tide-influenced environments and tidal fiat variability in the North American Midcontinent, *in* D. McIlroy, ed., The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society (London) Special Publication 228, p. 157-178.

Martin, M. A., and J. E. Pollard, 1996, The role of trace fossil (ichnofabric) analysis in the development of depositional models for the Upper Jurassic Fulmar Formation of the Kittiwake Field (Quadrant 21 UKCS), *in* A. Hurst, H.D. Johnson, S.D. Burley, A.C. Canham, and D.S. Mackertich, eds., Geology of the Humber Group: Central Graben and Moray Firth, UKCS: Geological Society (London) Special Publication 114, p. 163-183.

Martinius, A.W., I. Kaas, A. Næss, G. Helgesen, J.M. Kjaerefjord, and D.A. Keith, 2001, Sedimentology of the heterolithic and tide-dominated Tilje Formation (Early Jurassic, Halten Terrace, offshore nid-Norway), *in* O.J. Martinsen, T. Dreyer, eds., Sedimentary Environments Offshore Norway - Paleozoic to Recent: Norwegian Petroleum Foundation Special Publication 10, p. 103–144.

McAlpine, K.D., 1990, Mesozoic stratigraphy, sedimentary evolution, and petroleum potential of the Jeanne d'Arc Basin, Grand Banks of Newfoundland: Geological Survey of Canada, v. 89, p. 17-50.

McIlroy, D. 2004a, A review of ichnological concepts, methodologies, applications and frontiers, *in* D. McIlroy, ed., The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society (London) Special Publication 228, p. 3-27.

McIlroy, D. 2004b, Ichnofabrics and sedimentary facies of a tide-dominated delta; Jurassic Ile Formation of Kristin Field, Haltenbanken, offshore mid-Norway, *in* D. McIlroy, ed., The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society (London) Special Publication 228, p. 237-272.

McIlroy, D. 2004c, The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society (London) Special Publication 228, 479 pp.

McIlroy, D., 2007, Lateral variability in shallow marine ichnofabrics: implications for the ichnofabric analysis method: Journal of the Geological Society of London, v. 164, p. 359-369.

McIlroy, D., 2008, Ichnological analysis: The common ground between ichnofacies workers and ichnofabric analysts: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270, p. 332-338.

McIlroy, D., S. Flint, J.A. Howell, and N. Timms, 2005, Sedimentology of the tide-dominated Jurassic Lajas Formation, Neuquén Basin, Argentina, *in* G.D. Veiga, L.A. Spalletti, J.A. Howell, and E. Schwarz, eds., The Neuquén Basin, Argentina; a case study in sequence stratigraphy and basin dynamics: Geological Society (London) Special Publication 252, p. 83-107.

Meyer, R., and F.F. Krause, 2006, Permeability anisotropy and heterogeneity of a sandstone reservoir analogue: an estuarine to shoreface depositional system in the Virgelle Member, Milk River Formation, Writing-on-Stone Provincial Park, southern Alberta: Bulletin of Canadian Petroleum Geology, v. 54, p. 301-318.

Middleton, G.V., 1973, Johannes Walther's law of the correlation of facies: GSA Bulletin, v. 84, p. 979-988.

Nittrouer, C.A., and L.D. Wright, 1994, Transport of particles across continental shelves: Review of Geophysics, v. 32, p. 85-113.

Nickell, L.A., and R.J.A. Atkinson, 1995, Functional morphology of burrows and trophic modes of three thalassinidean shrimp species, and a new approach to the classification of thalassinidean burrow morphology: Marine Ecology Progress Series, v. 128, p. 181-197.

Orton, G.J., and H.G. Reading, 1993, Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size: Sedimentology, v. 40, p. 475–512.

Pemberton, S.G., and M.K. Gingras, 2005, Classification and characterizations of biogenically enhanced permeability: AAPG Bulletin, v. 89, p. 1493-1517.

Pemberton, S.G., M. Spila, A.J .Pulham, T. Saunders, J.A. MacEachern, D. Robbins, and I.K. Sinclair, 2001, Ichnology and sedimentology of shallow to marginal marine systems: St John's, Geological Association of Canada, 343 pp.

Pemberton, S.G., R.W. Frey, M.J. Ranger, and J.A. MacEachern, 1992, The conceptual framework of ichnology; Applications of ichnology to petroleum exploration; a core workshop: SEPM Core Workshop Notes 17, p. 1-32.

Pemberton, S.G., J.A. MacEachern, M.K. Gingras, and T.D.A. Saunders, 2008, Biogenic chaos: cryptobioturbation and the work of sedimentologically friendly organisms: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270, p. 273-279.

Phillips, C., D. McIlroy, and T. Elliot, 2011, Ichnological characterization of Eocene/Oligocene turbidites from the Grès d'Annot Basin, French Alps, SE France: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 300, p. 67-83.

Pianka, E.R., 1970, On r and k selection: American Naturalist, v. 104, p. 592-597.

Pittman, E.D., 1979, Porosity, diagenesis and productive capability of sandstone reservoirs, *in* P.A. Scholle, and P.R. Schluger, eds., Aspects of Diagenesis: SEPM Special Publication 26, p. 159-173.

Pickerill,R.K., and P.J. Brenchley, 1991, Benthic macrofossils as paleoenvironmental indicators in marine siliciclastic facies: Geoscience Canada, v. 18, p. 119-138.

Pollard, L.E., R. Goldring, and S.G. Buck, 1993, Ichnofabrics containing *Ophiomorpha*: significance in shallow-water facies interpretation: Journal of the Geological Society of London, v. 150, p. 149–164.

Posamentier, H.W., and R.G. Walker, 2006, Facies Models Revisited: Tulsa, SEPM Special Publication 84, 532 pp.

Pryor, W.A., 1975, Biogenic sedimentation and alteration of argillaceous sediments in shallow marine environments: GSA Bulletin, v. 86, p. 1244-1254.

Reading, H.G., 1996, Sedimentary Environments and Facies: Oxford, Blackwell Science, 688 pp.

Reading, H.G., and J.D. Collinson, 1996, Clastic coasts. *in* H.G. Reading, ed., Sedimentary Environments and Facies: Oxford, Blackwell Science, p. 154–231.

Richards, P.C., 1992, An introduction to the Brent Group: a literature review, *in* A.C. Morton, R.S. Haszeldine, M.R. Giles, and S. Brown, eds., Geology of the Brent Group: Geological Society (London) Special Publication 61, p. 15-26.

Savrda, C.E., and D.J. Bottjer, 1989, Trace-fossil model for reconstructing oxygenation histories of ancient marine bottom waters; application to Upper Cretaceous Niobrara Formation, Colorado: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 74, p. 49-74.

Savrda, C.E., and D.J. Bottjer, 1991, Oxygen-related biofacies in marine strata: an overview and update, *in* R.V. Tyson, and T.H. Pearson, eds., Modern and ancient continental shelf anoxia: Geological Society (London) Special Publication 58, p. 201–219.

Seilacher, A., 1964, Sedimentological classification and nomenclature of trace fossils: Sedimentology, v.3, p. 253-256.

Seilacher, A., 1967a, Bathymetry of trace fossils: Marine Geology, v. 5, p. 413-428.

Seilacher, A., 1967b, Fossil behaviour: Scientific American, v. 217, p. 72-80.

Seilacher, A., 1978, Use of trace fossil assemblages for recognizing depositional environments, *in* P.B. Basan, ed., Trace Fossil Concepts: SEPM Short Course Notes 5, p. 175-201.

Sheehan, P.M., and D.R.J. Schiefelbein, 1984, The trace fossil *Thalassinoides* from the Upper Ordovician of the eastern Great Basin: deep burrowing in the early Paleozoic: Journal of Paleontology, v. 58, p. 440-447.

Smith, L.B., G.P. Eberli, J.L. Masaferro, and S. Al-Dhahab, 2003, Discrimination of effective from ineffective porosity in heterogeneous Cretaceous carbonates, Al Ghubar Field, Oman: AAPG Bulletin, v. 87, p. 1509-1529.

Spila, M.V., S.G. Pemberton, B. Rostron, and M.K. Gingras, 2007, Biogenic textural heterogeneity, fluid flow and hydrocarbon production: bioturbated facies Ben Nevis Formation, Hibernia Field, Offshore Newfoundland, *in* J.A. MacEachern, K.L. Bann, M.K. Gingras, and G.S. Pemberton, eds., Applied Ichnology: SEPM Short Course Notes 52, p. 363-380.

Suchanek, T., 1985, Thalassinid shrimp burrows: ecological significance of species-specific architecture: Proceedings of the 5th International Coral Reef Congress, Tahiti, v. 5, p. 205-210.

Swinbanks, D.D., and J.L. Luternauer, 1987, Burrow distribution of Thalassinidean shrimp on a Fraser Delta tidal flat, British Columbia: Journal of Paleontology, v. 61, p. 315-332.

Taylor, A.M., and R.L. Gawthorpe, 1993, Application of sequence stratigraphy and trace fossils analysis to reservoir description; examples from the Jurassic of the North Sea, *in* J.R. Parker, ed., Petroleum geology of Northwest Europe: Proceedings of the 4th conference: The Geological Society of London, p. 317-335.

Taylor, A.M., and R., Goldring, 1993, Description and analysis of bioturbation and ichnofabric: Journal of the Geological Society, London, v. 150, p. 141-148.

Taylor, A.M., and R. Goldring, and S. Gowland, 2003, Analysis and application of ichnofabrics: Earth-Science Reviews, v. 60, p. 227-259.

Tonkin, N.S., D. McIlroy, R. Meyer, and A. Moore-Turpin, 2010, Bioturbation influence on reservoir quality: a case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada: AAPG Bulletin, v. 94, p. 1059-1078.

Van Wagoner, J.C., H.W. Posamentier, R.M. Mitchum, P.R. Vail, J.F. Sarg, T.S. Loutit, and J. Hardenbol, 1988, An overview of sequence stratigraphy and key definitions, *in*, C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner, eds., Sea Level Changes—An Integrated Approach: SEPM Special Publication 42, p. 39–45.

Walker, R.G., 1992, Facies, facies models and modern stratigraphic concepts, *in* R.G. Walker, and N.P. James, eds., Facies models: response to sea level change: St John's, Geological Association of Canada, p. 1-14.

Walker R.G., and N.P. James, 1992, Facies models: response to sea level change: St John's, Geological Association of Canada, 454pp.

Wetzel, A., and A. Uchman, 2001, Sequential colonization of muddy turbidites in the Eocene Beloveza Formation, Carpanthians, Poland: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 168, p. 171-186.

Wheatcroft, R.A. 1990, Preservation potential of sedimentary event layers. Geology, v. 18, p. 843-845.

Wheatcroft, R.A., and D.E. Drake, 2003, Post-depositional alteration and preservation of sedimentary event layers on continental margins; the role of episodic sedimentation: Marine Geology, v. 199, p. 123-137.

Wright, L.D., 1977, Sediment transport and deposition at river mouths: a synthesis: Geological Society of America Bulletin, v. 88, p. 857–868.

Chapter 2: Bioturbation influence on reservoir quality: A case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada

Abstract

The delineation well Ben Nevis L-55, located in the Hebron-Ben Nevis Field, offshore Newfoundland, targeted the Cretaceous Ben Nevis Formation in the petroleum-rich Jeanne d'Arc Basin. This case study focuses on the bioturbated net-pay horizons, and assesses the importance of animal-sediment interactions in controlling the porosity and permeability of sandstone reservoir intervals. In this study bioturbation can either reduce permeability and porosity by as much as approximately 33% or enhance by up to 600%, dependent on burrow type and behaviour of the trace-making organism.

The net-pay interval in the cored interval of Ben Nevis L-55 is characterized by *Ophiomorpha*-dominated ichnofabrics. The action of bioturbators can be classified in terms of sediment mixing, sediment cleaning, sediment packing and pipe-work building strategies. Bioturbation has the potential to: 1) increase isotropy or uniformity of grain-size by destroying sedimentary laminae through burrow homogenization; or 2) decrease isotropy by selectively sorting grains into burrow lining and fill by grain size, and through creation of open burrow systems filled with later sediments of differing character to the host sediment. The petrophysical characteristics of bioturbated reservoir facies are highly

dependent on lithology, trace fossil morphology, presence or absence of burrow linings, nature of burrow fills, burrow size and bioturbation intensity. Mudstone-rich facies and ichnofabrics containing mudstone-filled and/or lined burrows (e.g., *Ophiomorpha* and clusters of *Chondrites*) have the net-effect of permeability reduction. In contrast, permeability enhancement is documented from muddy sandstone facies with clean sand-filled burrows (e.g., *Thalassinoides*), and clean sandstones with burrow-mottled or diffuse to massive textures.

2.1 Introduction

Many of the world's most productive siliciclastic petroleum reservoirs are strongly bioturbated, including the Early Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada; Late Jurassic Fulmar Formation and Middle Jurassic Brent Group, North Sea, UK; Middle Jurassic Ile Formation, Halten Terrace, offshore mid-Norway; and Early Cretaceous McMurray Formation, Alberta, Canada (McAlpine, 1990; Richards, 1992; Cannon and Gowland, 1996; McIlroy, 2004; Crerar and Arnott, 2007). Effective production of hydrocarbon reservoirs requires reliable prediction of facies-related reservoir properties and correlation at the inter-well scale. Hence, specifically in bioturbated settings, facies analysis and reservoir characterization are reliant upon description and interpretation of bioturbation and ichnofabrics from conventional core (Martin and Pollard, 1996).

Ichnofabric analysis is an approach used to describe the sedimentology and ichnology of a horizon in terms of diversity, bioturbation intensity and colonization history (Bromley and Ekdale, 1986; Taylor and Goldring, 1993; Taylor *et al.*, 2003). An integrated approach to the prediction of reservoir quality in bioturbated reservoir intervals involves study of ichnofabric in core and further laboratory-based analysis. The same principles have also been used to improve the productivity of aquifers (Cunningham *et al.*, 2009).

This research is aimed at generating a more complete understanding of the role that organisms have in controlling the porosity and permeability of sandstone reservoirs at the reservoir scale. The studied core (BN L-55) was taken from Ben Nevis Field, in which the primary reservoir target is the Ben Nevis Formation. This sandstone-dominated reservoir is variably intensely bioturbated, with intensity of bioturbation being strongly facies controlled. *Ophiomorpha* are the most conspicuous element of the ichnofauna throughout the well, and are characteristic of several net-pay intervals. This study is focused on reservoir quality changes directly associated with *Ophiomorpha* ichnofabrics.

In order to determine the influence that bioturbation has on petrophysical properties, 129 meters of core were studied ichnologically and sedimentologically. Core descriptions are supplemented by ichnofabric analysis, and detailed petrophysical analysis of net-pay horizons. Bioturbated reservoir zones from the Ben Nevis L-55 core were studied using the following techniques: 1) core logging from both a sedimentological and ichnological (ichnofabric assignment) perspective, including visual estimation of bioturbation intensity; 2) creation of large thin slices (*sensu* Garton and McIlroy, 2006);

3) probe-permeametry; and, 4) porosity estimated using dye-impregnated petrographic thin sections and digital imaging software.

2.2 Regional setting

The Jeanne d'Arc Basin, offshore Newfoundland contains several petroleum reservoirs in three presently producing fields (Hibernia, Terra Nova and Whiterose), with the Hebron-Ben Nevis Field slated to come on-stream next. The basin is located approximately 350 km southeast of St. John's, Newfoundland, on the northeast Grand Banks (Figure 2.1). The Jeanne d'Arc Basin developed in response to three rifting episodes that took place during the late Triassic to early Cretaceous (Hubbard *et al.*, 1985; Tankard and Welsink, 1987; Sinclair, 1988). The Ben Nevis Formation was deposited during the last documented episode of rifting (Sinclair, 1993). The base of the Ben Nevis Formation is marked by the mid-Aptian Unconformity, which has been related to uplift and erosion during continental break-up (Tankard and Welsink, 1987; Tankard *et al.*, 1989).

The Ben Nevis Field is part of the Hebron-Ben Nevis complex of fault blocks, offshore Newfoundland, Canada (Figure 2.1). The field was discovered in July 1980 and currently has two wells drilled to date. The discovery well, Mobil *et al.* Ben Nevis I-45 (1980) drilled multiple targets from the Ben Nevis to the Hibernia Formation, while the delineation well Chevron *et al.* Ben Nevis L-55 (1999) targeted the Ben Nevis Formation alone. Ben Nevis L-55 was drilled to a vertical sub-sea depth of 2650 m, from which 129

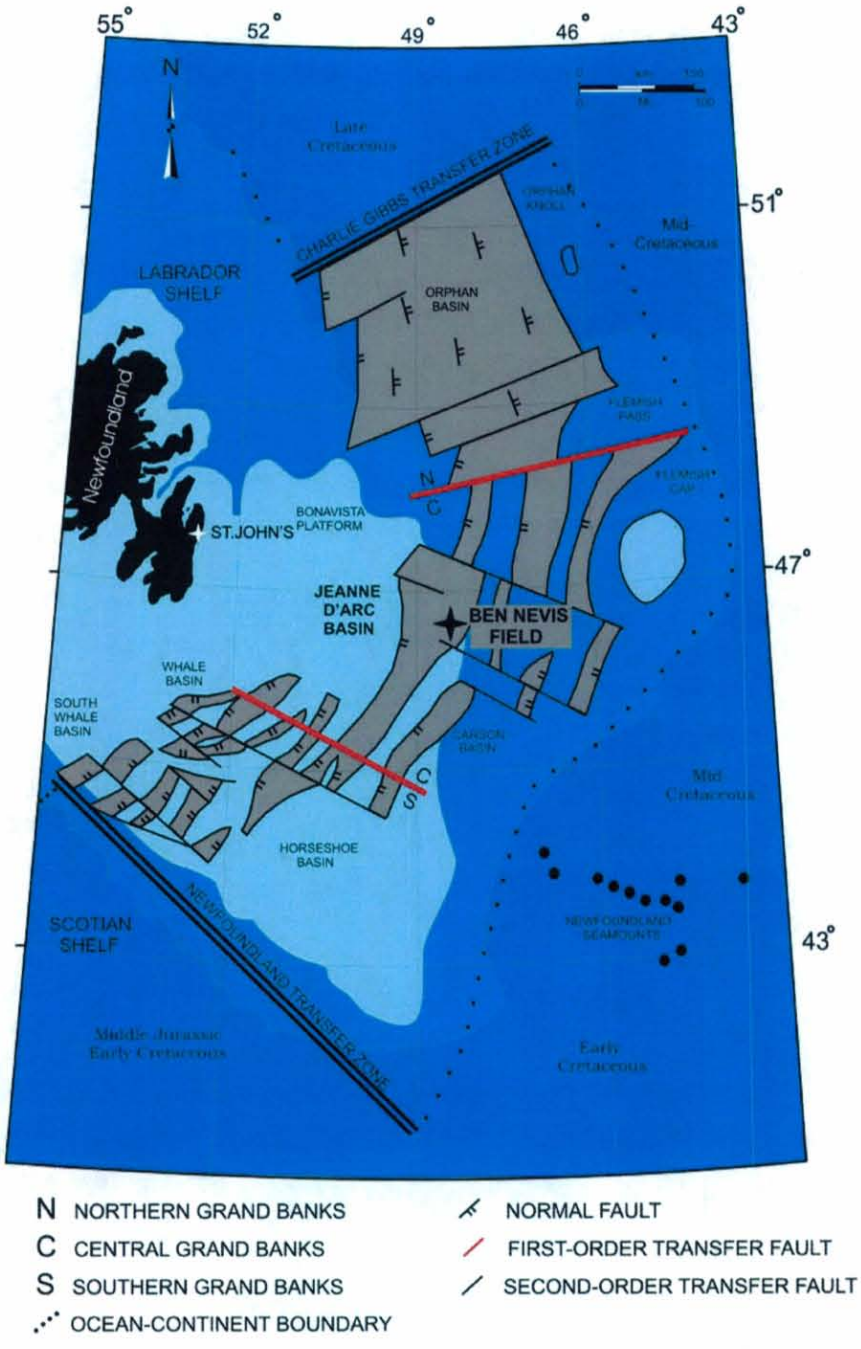


Figure 2.1. Sedimentary basins of the Grand Banks, offshore Newfoundland, Canada; including the Ben Nevis Field within the petroleum-rich Jeanne d'Arc Basin. The rift basins are separated from the Scotian and Labrador shelves by the Newfoundland and Charlie Gibbs fracture zones respectively (modified after Tankard & Welsink, 1987).

m of core were recovered from the upper Ben Nevis Formation between 2320 m and 2452 m vertical sub-sea depth. The base of the Ben Nevis Formation was not drilled at the L-55 location. The cored interval includes 82 m of net porous sandstone with a net-to-gross ratio of 29%, based on a petrophysical cut-off of 15%. Most of the net-porous sandstone occurs in bioturbated intervals, and concentrated in the lower half of the core (Table 2.1). The Ben Nevis Field is estimated to contain resources of 429 bcf of gas and 114 mbbls oil within 3 petroleum reservoirs: 1) the Ben Nevis Formation; 2) the Eastern Shoals Formation; and 3) the Hibernia Formation (C-NLOPB, 2008).

The Kimmeridgian Egret Formation is recognized as the primary source rock in the Jeanne d'Arc basin reservoirs, an organic-rich shale deposited in euxinic conditions (von der Dick, 1989). The terrestrial organic-rich Gambo Member forms the base of the Ben Nevis Formation, and it is suggested that this is the source of carbonaceous debris within the upper part of the formation (Sinclair, 1993). The fining-upward shallow marine succession is overlain by the transgressive marine Nautilus Shale (McAlpine, 1990), which acts as a reservoir seal. A back barrier-shoreface depositional setting for the Ben Nevis Formation was first proposed by Sinclair (1988, 1993).

Bioturbation is recognized in the Ben Nevis Formation (Tankard and Welsink, 1987; Sinclair, 1988, 1993; McAlpine, 1990; Driscoll *et al.*, 1995; Hesse and Abid, 1998; Pemberton *et al.*, 2001; Spila *et al.*, 2007), but has not previously been directly linked with improved reservoir quality. Highly bioturbated sandstones and siltstones of the Ben Nevis Formation of the Hibernia Field have been interpreted as shoreface sandstones and tidal inlet channels in a barrier island system (Tankard and Welsink, 1987; Sinclair 1993).

Table 2.1. Ben Nevis L55 core interval summary of lithofacies, ichnofabric, bioturbation intensity, and an idealized graphic log*

Graphic Log	Lithofacies	Ichnofabrics	Bioturbation Intensity	Core Plug Analysis		Core Slab Samples	
				Porosity (%)	Permeability (mD)	Porosity (%)	Permeability (mD)
Fairweather Deposition	Bioturbated sandy mudstone (LF 5)	*Ophiomorpha*-dominated, *Ophiomorpha-Phycosiphon*, *Ophiomorpha-Asterosoma* and *Teichichnus-Phycosiphon*.	60 to >90%	15.7 (6) 10.5 to 20.3	15.8 (6) <0.1 to 63.4	Not sampled	Not sampled
Event Bed Deposition	Laminated mudstone and sandstone (LF 4)	*Ophiomorpha-Chondrites-Phycosiphon*, *Thalassinoides-Planolites* and *Phycosiphon*-dominated.	1 to 60%	15.3 (7) 9.2 to 19.8	6.7 (7) 1 to 41.51	16.8 (Sample 5) 4.9 (Sample 4)	45.71 (Sample 5) 11.06 (Sample 4)
	Bioclastic horizon (LF 3)	Spreiten burrow.	1 to 5%	10.6 (9) 2.4 to 18.8	28.3 (9) <0.1 to 208	Not sampled	Not sampled
	Massive to low-angle bedded sandstone (LF 2)	*Ophiomorpha-Chondrites-Phycosiphon*.	60 to 90%	21.7 (7) 18.3 to 24.1	245.2 (7) 54.1 to 561	Not sampled	Not sampled
Fairweather Deposition	Bioturbated sandstone with common shell material (LF 1)	*Ophiomorpha*-dominated, *Ophiomorpha-Phycosiphon* and Burrow Mottled.	60 to >90%	16.4 (12) 12 to 22.7	73.1 (12) 0.1 to 376	23.4 (Sample 3) 27.2 (Sample 2) 20.3 (Sample 1)	18.33 (Sample 3) 9.32 (Sample 2) 79.36 (Sample 1)

*Core-plug data porosity and permeability measurements (mean, number of samples, range) (Core Laboratories Canada Ltd., 1999), with comparable core-slab sample probe-permeater measurements (TEMCO Inc. MP-401) and porosity measurements from Digital Analysis (Simple PCI).

Detailed ichnological and sedimentological study of the Avalon and Ben Nevis formations, based on nine wells in the Jeanne d'Arc Basin, allowed recognition of a number of depositional settings including fluvio-deltaic, tidal flats, salt marsh, barrier island to lagoon, and shoreface to offshore environments (Pemberton *et al.*, 2001). Ichnofacies recognized from the shoreface and embayment settings in the upper Ben Nevis Formation fall within the *Skolithos* and *Cruziana* Ichnofacies, and include recognition of several "*Glossifungites* surfaces" (Pemberton *et al.*, 2001). To date there has been no published sedimentological or ichnological study undertaken on the Ben Nevis L-55 core.

2.3 Methods

Three methods were used to describe the influence of bioturbation on porosity and permeability on five centre-cut core slab samples taken from the net pay zone in the Ben Nevis L-55 core interval: large thin slicing; conventional thin sections; and probe-permeametry. Two slices, 3-5 mm thick were removed from the core slab face of each sample; one for preparation of a large thin slice to study lithological contrasts between burrows and host matrix (Garton and McIlroy, 2006), and another slice to make blue epoxy-impregnated thin sections to visually estimate porosity and sorting. The core slab surface was divided into a grid (Dreyer *et al.*, 1990) and spot permeability data were obtained using a steady-state probe-permeameter (TEMCO Inc. MP-401). Porosity measurements are unstressed (e.g., in ambient laboratory conditions, not at calculated

reservoir confining stresses), and permeabilities are unstressed horizontal air permeabilities.

2.3.1 Thin Section Analysis

Thin sections (2.5 cm by 4.5 cm) were cut from a slice of the core slab face. The sample was then impregnated with blue epoxy resin, in order to highlight pore spaces when viewed under the microscope (Figures 2.2 and 2.3). Visual estimates of sorting were measured using comparison charts (Jerram, 2001). Digital image analysis software (Simple PCI®) is used to calculate the relative proportions of 'blue' pore space in a given area of interest, and this 2D visual measurement is taken as a proxy for the corresponding porosity.

2.3.2 Large Thin Slicing

The technique of large thin slicing is used to study the sedimentary and biogenic fabrics in sandstone and mudstone lithologies in transmitted light (Garton and McIlroy, 2006). When viewed in transmitted light, the large thin slices display sedimentary structures and detailed ichnology not otherwise visible in polished hand specimen or field samples (Figures 2.4 and 2.5).

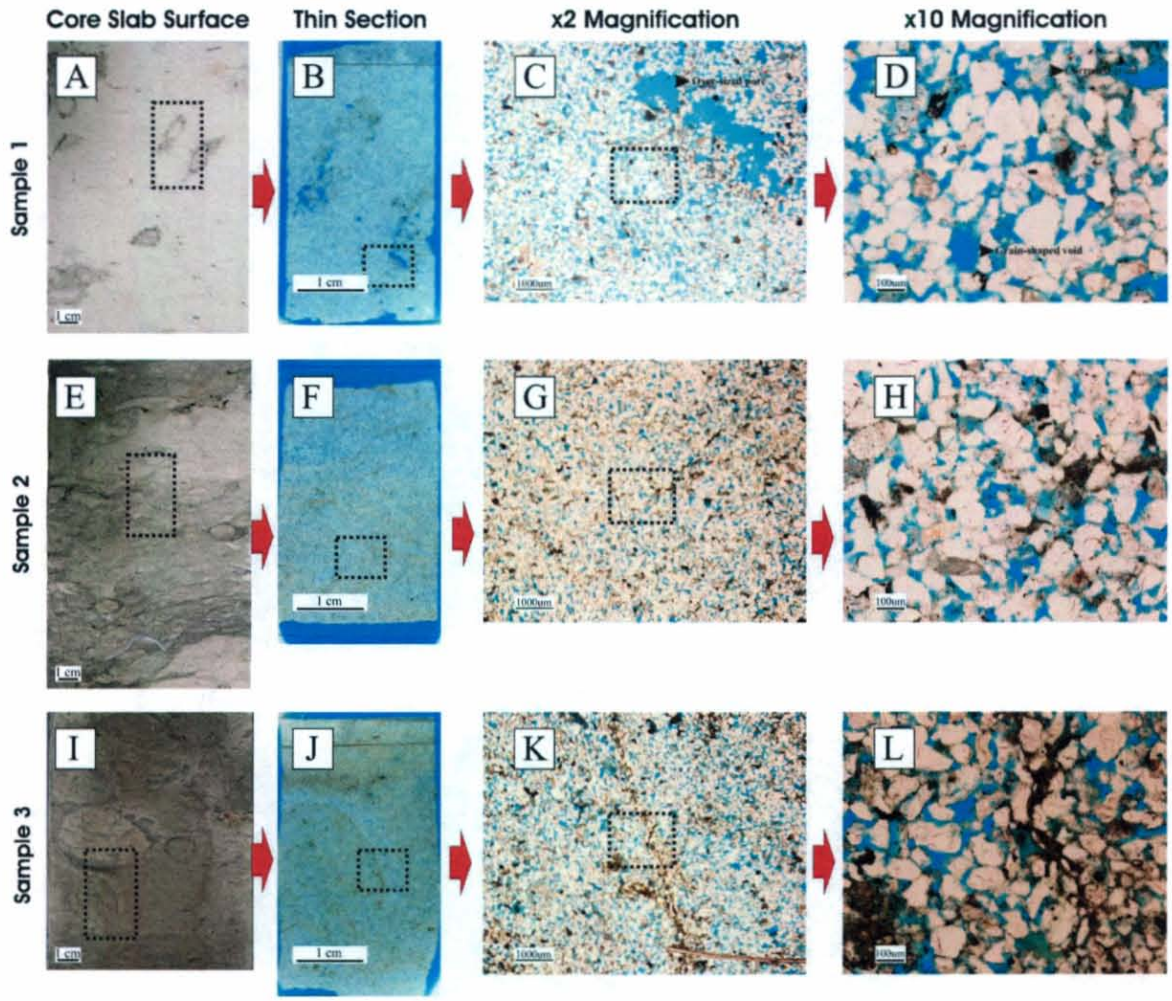


Figure 2.2. Porosity and petrographic details of samples 1, 2 and 3 from bioturbated sandstone lithofacies 1 (LF1) taken from Ben Nevis L-55 core slab interval 2475m to 2388m. Thin sections (B-D, F-H and J-L) are impregnated with blue epoxy, grey color shows pore space, off-white colors are quartz grains and dark colors are organic matter, clay minerals or pyrite. Dashed black rectangles (A, E, I) delineate where thin section samples were taken and dashed black boxes (B, C, F, G, J and K) delineate where plane-polarized light photomicrographs were taken. (A) Core slab sample 1 (2475m) with intense bioturbation (>90%) and *Ophiomorpha* burrows. (B) Oversized pores are concentrated at *Ophiomorpha* burrow margins. (C) Close-up of large grey oversized pores. (D) Inter-particle porosity (grey), corroded grains and grain-shaped voids. Sample porosity is 20.3%. (E) Core slab sample 2 (2460m) with intense bioturbation (>90%) and *Ophiomorpha* burrows. (F) Burrow mottled texture. (G) Quartz-rich very fine sandstone. (H) Inter-particle porosity (grey) and pore-filling clay minerals. Sample porosity is 27.2%. (I) Core slab sample 3 (2388m) with intense bioturbation (>90%), *Ophiomorpha* and *Thalassinoides*. (J) Clean sand *Thalassinoides* burrow halo and mudstone-rich *Ophiomorpha* burrow lining. (K) Close-up of *Thalassinoides* burrow margin. (L) Inter-particle porosity (grey), clay over-growths and pore-filling clay minerals concentrated in burrow lining. Sample porosity is 23.4%.

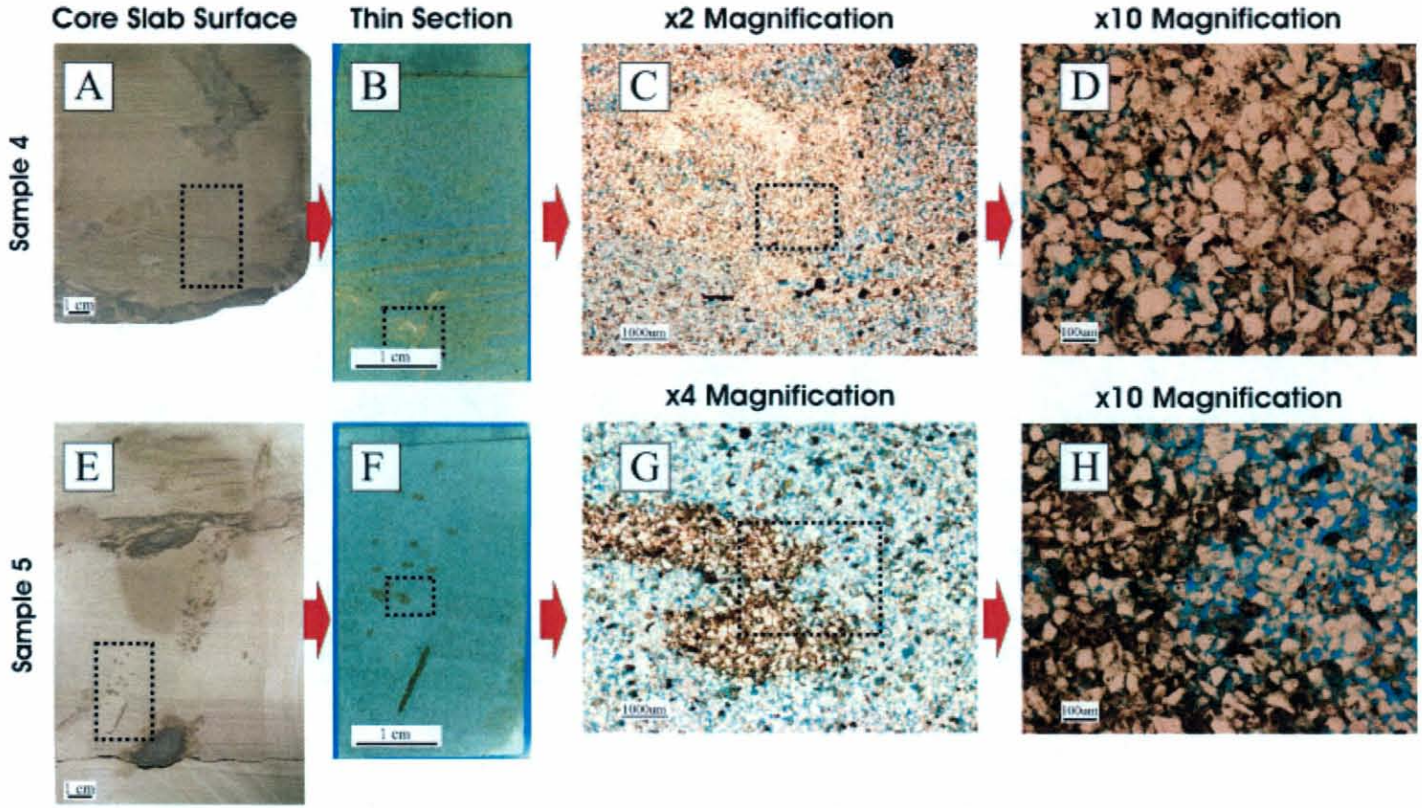
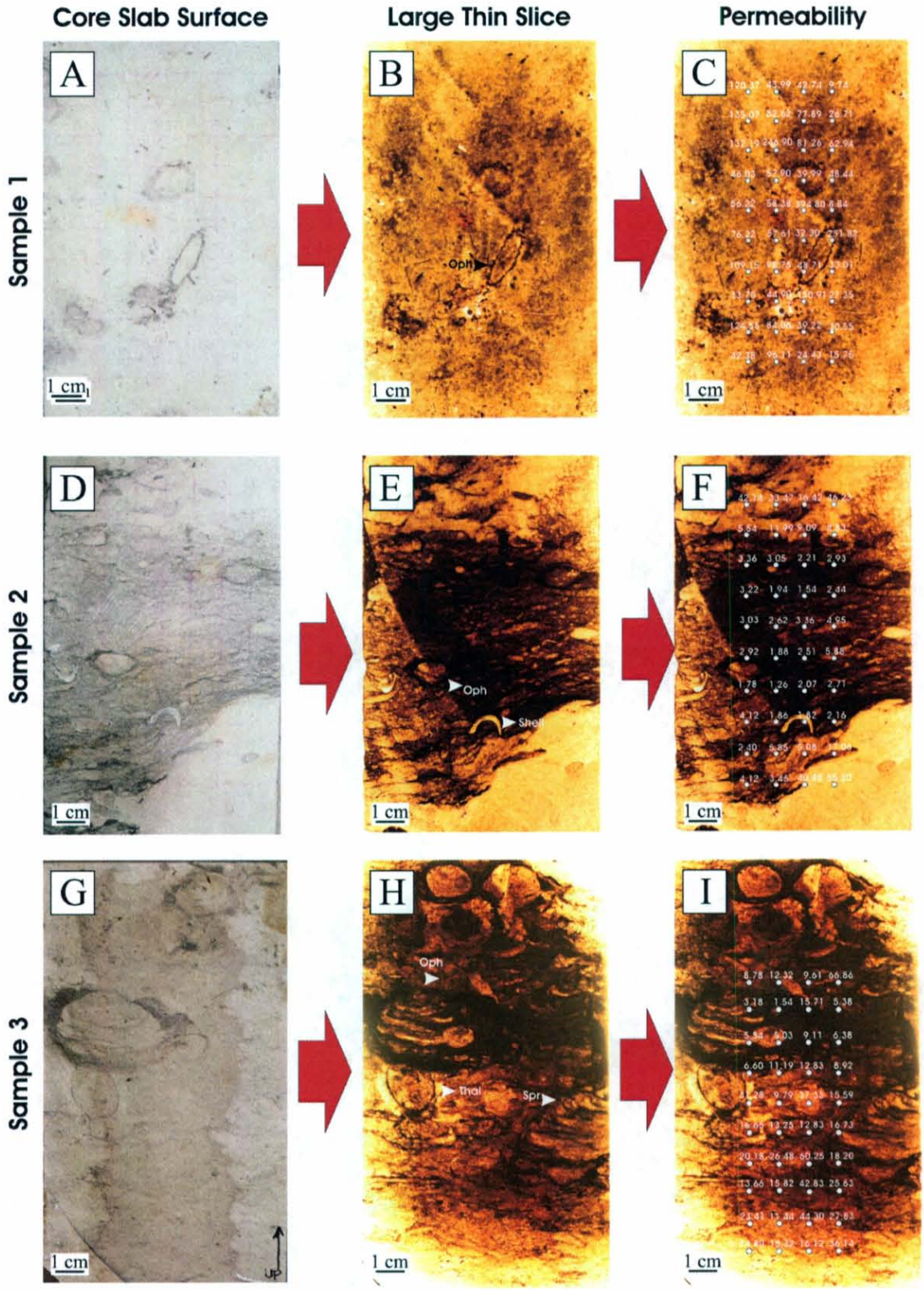


Figure 2.3. Porosity and petrographic details of samples 4 and 5 from bioturbated mud-rich sandstones lithofacies 4 (LF4) taken from Ben Nevis L-55 core slab interval 2357m 2356m. Thin sections (B-D, F-H) are impregnated with blue epoxy, grey color shows pore-space, off-white colors are quartz grains and dark colors are organic matter, clay minerals and pyrite. Dashed black rectangles (A, E) delineate where plane-polarized light photomicrographs thin section samples were taken and dashed black boxes (B, C, F, G) delineate where photomicrographs were taken. (A) Core slab sample 4 (2357m) with low bioturbation (5-30%), vertically oriented *Ophiomorpha* and laminae. (B) Diffuse laminae and indistinct burrow. (C) Close-up of clay-rich burrow lining. (D) Inter-particle porosity (grey) and pore-filling clay, calcite and clay cements occluding available pore space. Sample porosity is 4.9%. (E) Core slab sample 5 (2356m) with moderate bioturbation (30-60%), *Ophiomorpha* burrow, *Chondrites* burrows and laminae. (F) Mudstone-filled *Chondrites* burrows in mud-rich, diffusely laminated very fine sandstone. (G) Close-up of *Chondrites*. (H) Inter-particle porosity (grey) and pore-filling clay minerals in *Chondrites* burrow. Sample porosity is 16.8%.

Figure 2.4. Large thin slices and permeability data of samples 1, 2 and 3 from bioturbated fine sandstone (LF1), assigned an *Ophiomorpha*-dominated ichnofabric from Ben Nevis L-55 core interval, 2475m to 2388m. Core slab slices (A, D and G) and large thin slice images (B, E and H) with spot-permeability measurements overlain (C, F and I). (A) Core slab sample 1 (2475m). (B) *Ophiomorpha* (Oph) margins and concentrations of clay-filled pores of burrow mottled sandstone. (C) Permeability data points range from 8.84 mD to 394.80 mD. (D) Core slab sample 2 (2460m) of bioturbated fine sandstone with shell fragments. (E) Burrow mottled mud-rich sandstone and clean sandstone bed at base. (F) Permeability data points range from 1.54 mD to 55.20 mD. (G) Core slab sample 3 (2388m). (H) *Thalassinoides* (Thal) burrow halo, mud-pellet lined *Ophiomorpha* and spreiten burrow (Spr). (I) Permeability data points range from 1.54 mD to 66.86 mD.


Core Slab Surface
Large Thin Slice
Permeability
Sample 1
Sample 2
Sample 3
A
B
C
D
E
F
G
H
I
Oph
Shell
Thal
Spr
1 cm
UP

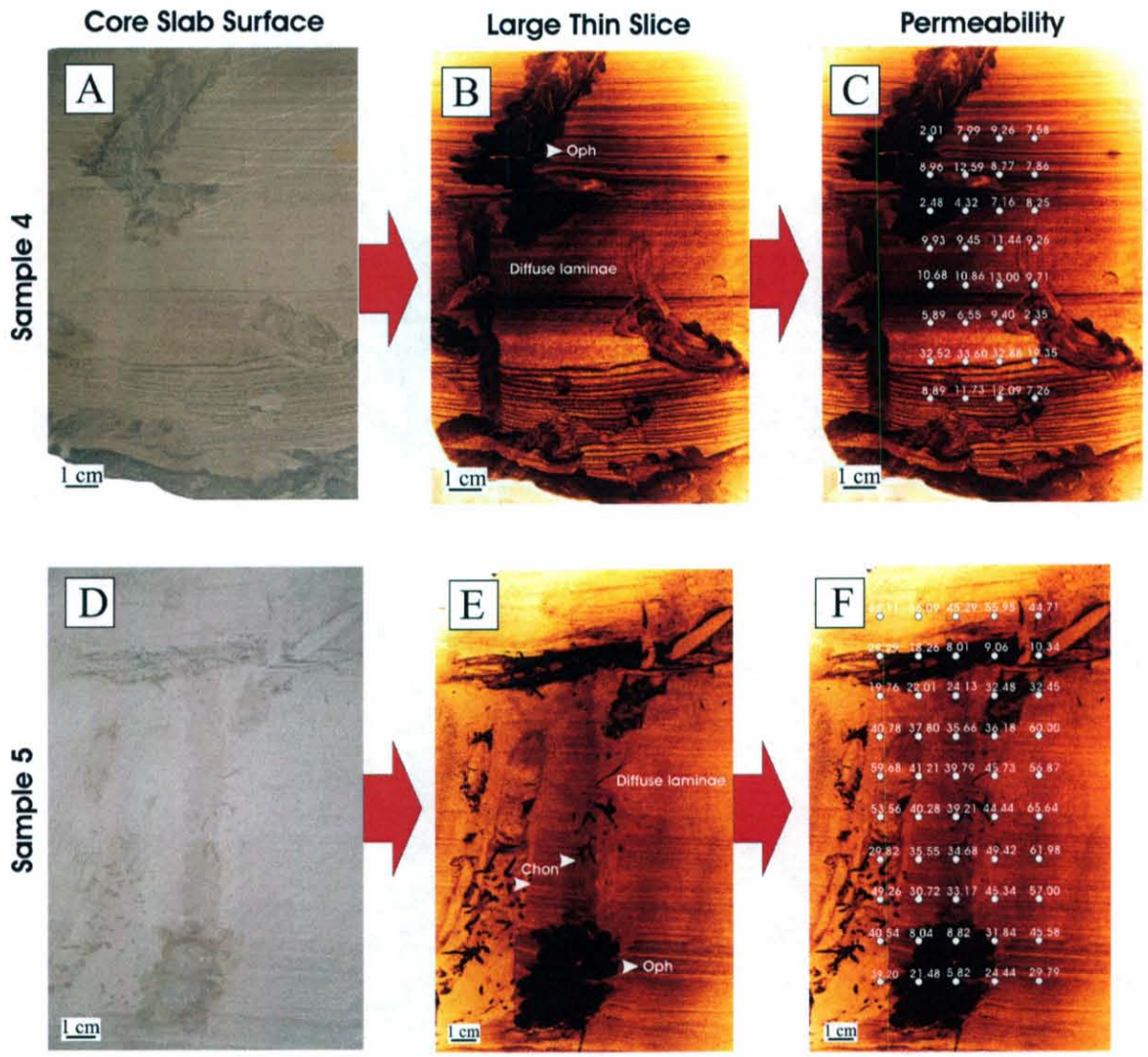


Figure 2.5. Large thin slices and permeability data of samples 4 and 5 from bioturbated mud-rich very fine sandstone (LF4), assigned an *Ophiomorpha-Chondrites-Phycosiphon* ichnofabric from Ben Nevis L-55 core interval, 2357m to 2356m. Core slab slices (A and D) and large thin slice images (B and E) with spot-permeability measurements overlain (C and F). (A) Core slab sample 4 (2357m). (B) Discrete *Ophiomorpha* (Oph) and indeterminate traces cross-cutting distinct and diffuse laminae. (C) Permeability data points range from 2.01 mD to 33.60 mD. (D) Core slab sample 5 (2356m). (E) *Chondrites* (Chon) burrows and pyritized *Ophiomorpha* burrows in diffusely laminated host sediment. (F) Permeability data points range from 5.82 mD to 65.64 mD.

2.3.3 Probe-Permeametry Data

The probe-permeameter (TEMCO Inc. MP-401) injects compressed nitrogen gas into the rock and, using a tip of 3.18-6.35 mm inner-outer diameter, measures the flow rate and injection pressure in a rock volume of approximately 1 cm^3. Permeability in millidarcies (mD) was calculated using the appropriate form of Darcy's equation modified by the half-space solution of a geometrical factor G_0 as a function of probe-tip seal thickness (Goggin *et al.*, 1988). In each of the five center-cut core slab samples, a 1 cm-grid was drawn on the surface, and spot permeability measurements were taken in the centre of each square. Four measurements were taken for each of 40 points on the grid to obtain an average (Figures 2.4C, 2.4F, 2.4I, 2.5C and 2.5F).

2.4 Sedimentology and Ichnology of Ben Nevis L-55

2.4.1 Sedimentology of Ben Nevis L-55

The Ben Nevis Formation in the L-55 well displays a net upward-fining trend, with mudstone content increasing upward. The cored interval is dominated by bioturbated fine-grained sandstones with shell lags and mudstone beds, grading into mud-rich very fine sandstone at the top of the cored interval (Table 2.1). Mudstone laminae, low-angle stratification, dispersed shell fragments (decreasing upwards), bioclastic beds and carbonaceous material are common throughout, along with rare mudstone rip-up clasts and sideritized mudstone clasts. A total of five lithofacies (LF) are defined herein:

LF1) bioturbated sandstone with shell material; LF2) low-angle cross-stratified sandstones; LF3) bioclastic sandstones; LF4) laminated very-fine-grained sandstones with mudstone; and, LF5) bioturbated mud-rich sandstones (Table 2.1 and Figure 2.6). Lithofacies 1 and 5 are intensely bioturbated, and contain disseminated carbonaceous matter and shell debris. Bioturbation intensity in LF1 and LF5 varies between 60 and 100%, but is typically about 75%. Lithofacies 2, 3, and 4 are sparsely to moderately bioturbated (1%-60%). Intensely bioturbated facies LF1 and LF5 are interpreted as fair-weather beds. Less intensely bioturbated sandstone and mudstone units are interpreted to be event beds deposited during periods of intense hydrodynamic activity in which bioturbation is exclusively post-depositional (cf. Aigner, 1985).

The dominant facies in the cored interval is LF1, highly bioturbated sandstones which contain dispersed shelly debris. The presence of coarse shelly lags (LF3) and pebble horizons at the base of bioturbated units suggests event bed deposition followed by bioturbation during protracted periods of low hydrodynamic energy. LF2 consists of fine-grained, low-angle, cross-laminated sandstones that are either unbioturbated or contain low to moderate levels of bioturbation (5-60% bioturbation). The cross laminae are considered to be either storm-induced hummocky cross-stratification (Dumas and Arnott, 2006) or suspension settling in mouth-bar settings (cf. Brettle *et al.*, 2004). Sections of the cross-laminated sandstone (LF4) show diffuse zones that may have formed biogenically by meiofaunal cryptobioturbation (Howard and Frey, 1975), or by small-scale physically-induced dewatering or liquefaction (Figure 2.6C; Owen, 1996; Hildebrandt and Egenhoff, 2007). The author considers it to be nearly impossible to distinguish between these possibilities for lack of objective recognition criteria. The

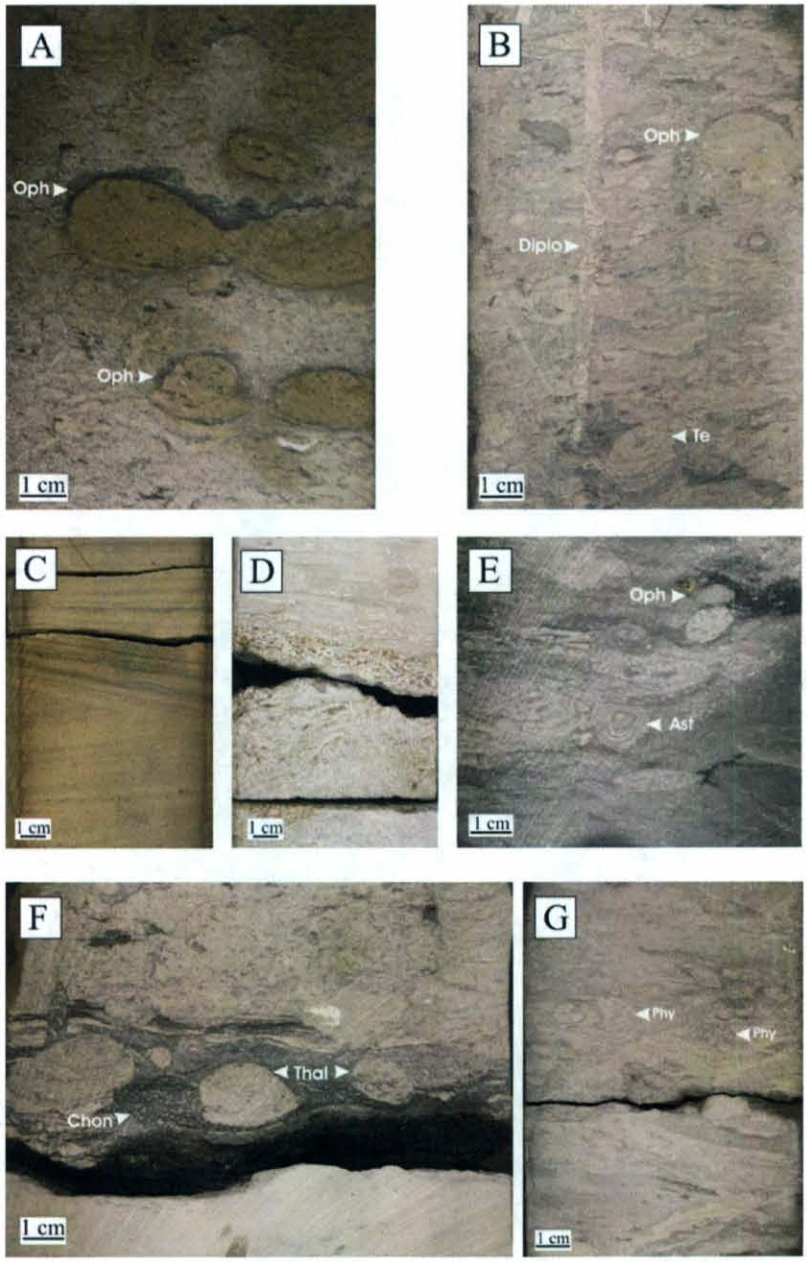


Figure 2.6. (A) *Ophiomorpha*-dominated ichnofabric in lithofacies 1 (LF1), note irregular mud pellets on roof of *Ophiomorpha irregulaire* burrow only. (B) *Ophiomorpha*-dominated ichnofabric with *Diplocraterion* (Diplo) and *Teichichnus* (Te) burrows in lithofacies 1 (LF1). (C) Low-angle cross-stratified sandstone lithofacies 2 (LF2). (D) Oyster and calcareous worm tube rich bioclastic horizon of lithofacies 3 (LF3). (E) *Ophiomorpha-Asterosoma* ichnofabric in upper sandy mudstone lithofacies 5 (LF5), *Asterosoma* (Ast). (F) *Thalassinoides* (Thal) and *Chondrites* (Chon) in laminated mudstone facies 4 (LF4) with *Thalassinoides-Planolites* ichnofabric, interbedded with bioturbated sandstone with shell material lithofacies 1 (LF1). (G) Clusters of mudstone-filled *Phycosiphon* burrows with sandy halo in *Phycosiphon*-dominated ichnofabric of lithofacies 4 (LF4).

bioclastic beds of LF3 comprise abundant broken, current-sorted bivalves (especially oysters), along with gastropods and serpulid worm tube segments (Figure 2.6D). The shell beds of LF3, are also commonly interbedded with LF1, either as erosively-based shell lags below sandstone beds or as up to 20 cm thick bioclastic beds with low sand content. The laminated sandstone and mudstone beds of LF2 are planar- or wavy-bedded, or diffusely laminated with partings defined by mud drapes. A basal mudstone-pebble lag, locally with oblate often sideritized, mudstone clasts and/or shell debris may be present. Alternations of planar laminae, diffuse laminae and structureless intervals in LF4 are interpreted as periods of variable sedimentation rates. Laminated mudstone beds (LF4) are commonly found to directly overlie cross-stratified sandstone (LF2) in the upper section of core interval. These mudstone beds are interpreted to represent rapid post-event bed deposition in paleoenvironments with low hydrodynamic energy. The mud-rich siltstone (LF5) contains the most intense and diverse levels of bioturbation within the cored interval. This highly bioturbated facies (LF5) is often intercalated with laminated horizons (LF4) and can be referred to as a "lam-scram" style of deposition (Howard, 1972). Laminated beds are deposited under high flow regime conditions, for example during storm events, followed by "scrambling" of the sediment by bioturbation during low energy post-event periods (Ekdale *et al.*, 1984). Coalified and pyritized wood clasts are common in all facies and may indicate proximity to a distributary system and/or transgressive reworking and erosion of the plant-rich Gambo Member (Sinclair, 1993).

The heterolithic nature of that portion of the Ben Nevis Formation cored at L55 is consistent with event bed deposition in an offshore setting. Event beds are thought to be

storm induced with evidence for fluvial influence on the system in the form of fluid mud deposits and plant-debris. Towards the top of the Ben Nevis succession in the L-55 core, the mudstone-rich facies (LF5) becomes dominant and this is taken to reflect an increase in relative sea level. In summary, deposition of the facies represented in the cored interval of Ben Nevis L-55 is thought to have occurred on a wave-dominated coastline with some fluvial influence. No back-barrier or lagoonal facies were identified. The depositional setting is perhaps best compared to that of a wave-dominated delta.

2.4.2 Ichnology of Ben Nevis L-55

A diverse assemblage of deposit- and suspension-feeding marine trace fossils are found in the cored interval. Ichnotaxa include (by first occurrence at base of core); *Ophiomorpha*, *Phycosiphon*, *Thalassinoides*, *Planolites*, *Chondrites*, *Diplocraterion*, *Teichichnus*, *Palaeophycus* and *Asterosoma* (Figure 2. 6). Indistinct burrow-mottling is also present throughout the core. Bioturbation intensity is extremely variable and is found to be facies-dependent (Table 2.1). Measurement of the common trace fossils shows that burrow diameters of *Ophiomorpha*, *Thalassinoides* and *Asterosoma* remain constant throughout the succession. This suggests that they were created by adult organisms, probably in an equable palaeoenvironmental setting. Rare escape traces exist and are associated with event beds; they are likely a result of organism entrainment during event bed flow and transport (cf. Föllmi and Grimm, 1990).

Ophiomorpha (5-50 mm diameter) is the most abundant and conspicuous trace fossil in the succession, visually dominates most of the described ichnofabrics in the

lower part of the L-55 core, and is an accessory component of ichnofabrics in many of the mudstone-rich beds at the top of the Ben Nevis Formation. *Ophiomorpha* are lined with circular to oval mudstone or organic-detritus-rich pellets. In several cases the pellets are only present on the roof of the burrow. Burrow fill is lithologically variable, and may comprise either a massive sandstone infill or a concentrically-laminated mudstone fill (Figures 2.2B-D, 2.3E 2.6A, 2.6B, 2.6F). The three-dimensional morphology of *Ophiomorpha* galleries are known to include boxworks, networks and mazes (Frey *et al.*, 1978). Many modern species of burrowing (*Ophiomorpha* and *Thalassinoides*-producing) crustaceans produce inter-connected burrow networks (Pryor, 1975). Analogous fossil burrow systems thus have the potential to produce enhanced permeability fabrics within sedimentary successions (Figures 2.4 and 2.5), though burrows with similar cross-sectional expressions may comprise isolated shafts and tunnels (e.g., Miller and Curran, 2001). This uncertainty regarding the degree to which the fossil burrows *Thalassinoides* and *Ophiomorpha* are in horizontal communication, and the macro-pore networks that they form, remains a problematic issue in some hydrocarbon reservoirs (Gingras *et al.*, 2007).

Unlined *Thalassinoides* (10-21 mm diameter) are common in Ben Nevis L-55, but are only clearly visible in mudstone-rich laminated beds (LF4) and mud-rich siltstone (LF5) (Figure 2.6F). Large thin slices created using the method of Garton and McIlroy (2006) reveal that *Thalassinoides* is actually present in all facies throughout the core (compare Figures 2.4G and 2.4I). The fill of *Thalassinoides* is commonly found to correspond to that of the lithology of the overlying colonization surface (Figure 2.6F). This is generally taken to indicate that the burrow was created as an open burrow, and

kept open with self-induced water currents (Sheehan and Schiefelbein, 1984). Modern thalassinid shrimps construct burrows that resemble *Thalassinoides* trace fossils with vertical shafts and horizontal to oblique galleries at depths of up to 1 m (Sheehan and Schiefelbein, 1984; Swinbanks and Luternauer, 1987). Sandstone-filled *Thalassinoides* create vertical and horizontal macropore networks in Ben Nevis L-55 with the potential to act as flow conduits in hydrocarbon reservoirs, but—as is the case with *Ophiomorpha*—isolated burrows may require mechanical fracturing in the horizontal plane to create reservoir flow units.

Mudstone-filled burrows of *Phycosiphon* (<1 mm diameter; Wetzel and Bromley, 1994) and *Chondrites* (1 to 2 mm diameter; Bromley and Ekdale, 1984) are common throughout the core interval (Figures 2.6F, 2.6G,) with the exception of the bioclastic horizons (LF3). Clusters of the trace fossils are generally horizontal or oblique and may overprint other traces such as *Ophiomorpha*. When present in clusters, these trace fossils may create localized low porosity patches in the host sediment.

Burrow-mottling is persistent throughout Ben Nevis L-55 core (Figures 2.6 and 2.5) and is often cross-cut by discrete burrows. These undeterminable biogenic structures are associated with repeated overprinting in horizons with intense bioturbation (>90%). This burrow-mottled texture is interpreted to reflect burrow homogenization of the primary sedimentary fabric, and may create zones of permeability enhancement relative to the host sediment (Meyer and Krause, 2006).

2.4.3 Bioturbation and Ichnofabric in Ben Nevis L-55

Event bed preservation (e.g., LF2, 3, 4) is a function of sedimentation rate, biogenic mixing rate, and event bed thickness (Wheatcroft, 1990; Bentley and Sheremet, 2003). In this study, event beds with low-angle cross-stratification, greater than around 10 cm in thickness, are found to greatly suppress bioturbation. Densely packed bioclastic beds are also generally found to be un-bioturbated (Figure 2.1).

Tiering of traces within the Ben Nevis Formation event beds includes rarely preserved shallow tier trace fossils such as *Diplocraterion*, perhaps by instantaneous casting (cf. Einsele and Seilacher, 1991; Figure 2.6B). In facies that are interpreted to represent slow continuous deposition (e.g., LF1 and 5), evidence for repeated overprinting can be recognized. Colonization order of trace-makers is difficult to determine as very few cross-cutting relationships are recognized. Nonetheless, *Diplocraterion* is seen cutting *Ophiomorpha*, *Phycosiphon* traces are overprinting *Ophiomorpha*, and all burrows cross-cut indistinct burrow-mottled ichnofabric. Shallow tier burrows are poorly preserved, and the ichnofabrics are dominated by mid to deep tier trace fossils (e.g., *Ophiomorpha*, *Thalassinoides*, *Phycosiphon* and *Chondrites*; cf. Bromley, 1990).

Nine discrete ichnofabrics (Table 2.1) have been recognized in Ben Nevis L-55, and have been categorized into either intensely bioturbated "fair-weather" or "event bed related" ichnofabric associations *sensu* McIlroy (2007). Ichnofabrics characterizing the fair-weather ichnofabric association (associated with bioturbated sandstone and siltstone, LF1 and LF5) are typically *Ophiomorpha*-dominated. Fair-weather ichnofabrics include

the: *Ophiomorpha-Phycosiphon*; *Ophiomorpha-Asterosoma*; *Teichichnus-Phycosiphon* and burrow-mottled ichnofabrics. The event bed related ichnofabrics are *Ophiomorpha-Chondrites-Phycosiphon* (associated with laminated sandstone, LF4 and the low-angle cross-stratified LF2); spreiten-burrow ichnofabric, associated with the bioclastic (LF3); *Thalassinoides-Planolites;* and the *Phycosiphon*-dominated ichnofabric of the laminated mudstone facies (LF4).

Core slab samples 1, 2 and 3 are of the *Ophiomorpha*-dominated fair-weather ichnofabric in the bioturbated sandstone facies (LF1; Figures 2.2 and 2.4). Samples 4 and 5 come from the laminated sandstone facies (LF4; Figures 2.3 and 2.5), and contain the *Ophiomorpha-Chondrites-Phycosiphon* event bed ichnofabric. On the basis of the data presented these two ichnofabrics are associated with improved reservoir quality in Ben Nevis well L-55. Detailed assessment of the host sediment has been undertaken in order to fully understand the impact of bioturbation on reservoir quality.

2.5 Porosity and Permeability in Ben Nevis L-55

The main controls on spot permeability contrasts are lithology and cementation, a simple and expected relationship between higher permeability sandstone and lower permeability mudstone, siltstone, muddy sandstone or cemented zones. Processes which affect the distribution of grain size fractions are the development of physical and biogenic structures. In the Ben Nevis L-55 core, mudstone-rich facies (LF4) and ichnofabrics containing mudstone-filled and/or lined burrows (e.g., *Ophiomorpha* and clusters of

Chondrites) have the net-effect of permeability reduction. In contrast, sandstone-rich facies (LF1 and LF2) with sandstone-filled burrows (e.g., *Thalassinoides*) and ichnofabrics with burrow-mottled or diffuse to massive textures have the net-effect of permeability enhancement.

The main pore type is inter-granular porosity, which has been reduced by pore-filling detrital clay, bioclasts, calcite cements and sedimentary lithoclasts. Thin section analysis reveals grain size sorting associated with sedimentary structures (e.g., laminae) and biogenic structures (trace fossils). Concentration of the clay to silt grade material into laminae, burrow linings and fill (e.g., *Ophiomorpha* and *Chondrites*; Figures 2.3 and 2.5) within sandstone decreases sorting of grains and therefore reduces porosity. This biogenic process can be described as sediment packing. Conversely, some mud lined burrows (e.g., *Thalassinoides*) create zones of biologically-cleaned sandstone, as mud and organic matter is preferentially removed from host sediment (23.4% and 31.28 mD; Figures 2.2I-L and 2.4I). Sorting and concomitant increased porosity is created by the process of sediment cleaning in these burrows. Burrow-mottled fabrics or diffuse to massive horizons are formed by the biogenic process of sediment mixing.

Anomalous permeability data points on large thin slice images that do not appear to be directly associated with any sedimentary or biogenic features on the slabbed surface, are suggested to be influenced by high permeability domains (e.g., burrows and dissolution voids) or low permeability zones (shells and pyrite) in the core that do not cut the two-dimensional surface (Figures 2.4C, 2.4D and 2.5F). In this regard it is important to remember that the probe-permeameter measurements reflect a three-dimensional sample volume which is only partially represented by slabbed surfaces.

2.5.1 Host Sediment Porosity and Permeability in Ben Nevis L55

All samples are predominantly fine to mud-rich very fine-grained sandstones. Sandstone composition is dominated by quartz grains, with lesser amounts of feldspar, calcite grains, lithic clasts, clay and organic detritus. Good inter-particle (primary) porosity is present between moderate to well-sorted, sub-angular to sub-rounded loosely packed grains (Figures 2.2 and 2.3). Porosity measured from blue-epoxy impregnated thin sections is between 4.9 and 27.2%. It is suggested the inter-granular pore space was preserved due to early calcite cementation, followed by subsequent dissolution of pore-filling cements (Hesse and Abid, 1998). The source of the early calcite cementation in the Ben Nevis Formation is through dissolution of bioclastic material from within the reservoir interval (Hesse and Abid, 1998). Secondary porosity can be recognized in the form of oversized pores, corroded grains, floating grains and grain-shaped voids in the sandstone (Figures 2.2D, 2.2H and 2.2L). This suggests that the secondary porosity is generated from dissolution of shell fragments, calcite cement, lithic clasts, clay minerals, and feldspar grains.

Physical sedimentary structures are absent in samples 1, 2 and 3 from the bioturbated fine sandstone facies (LF1) as a result of the intense bioturbation. High permeability values in Sample 1 are found in clean, mud-deficient sandstone-rich areas (Figures 2.4C, 2.4F and 2.4I). Lower permeability regions of Samples 2 and 3 correspond to mud-rich bioturbated sandstone with shell fragments (Figures 2.5C and 2.5F). Samples within this facies preserve no physical sedimentary structures, only

burrow-mottling with few discrete burrows visible. Samples 4 and 5 of the laminated sandstone facies (LF4) generally have well developed very fine (<1 mm-3 mm) planar and parallel mudstone laminae within very fine sandstone. The porosity and permeability of the host sediment is low due to well developed closely spaced mudstone laminae. The higher permeability data points of Sample 5 are a result of lower mud content in the laminated sandstone, and greater proportions of diffusely laminated to massive texture (Figure 2.5F).

2.5.2 Bioturbated Sediment Porosity and Permeability in Ben Nevis L-55

Burrowing organisms can secrete mucus as they move through the sediment; use mucus to trap organic matter or fine grains; or incorporate detritus (mud or sand) to create a burrow wall or lining (Bromley, 1990; Herringshaw *et al.*, 2010). Consequently burrows can alter the geochemistry of a substrate, acting as focal points for the colonization of microbes and mineralization, which may consequently drive early diagenetic processes (Bromley, 1990; Pemberton and Gingras, 2005). This bio-geochemical reaction may promote burrow-induced diagenesis, with pyrite (Figure 2.5E), siderite and calcite growth centered on the burrow (Pemberton and Gingras, 2005; Gingras *et al.*, 2007).

In highly bioturbated ichnofabrics from Lithofacies 1 (Figures 2.2 and 2.4), discrete traces are generally not preserved as a result of repeated overprinting. Samples 1, 2 and 3 of this facies preserve no original sedimentary fabric and are categorized as burrow-mottled. Porosity and permeability within the burrow-mottled sandstone are

enhanced relative to un-bioturbated sandstone by one or both of two animal-sediment interactions: 1) "sediment packing" the removal of silt-clay grade material from the host sediment, and re-depositing it in burrow linings and fills; 2) "sediment cleaning", the removal of silt-clay grade material from the sedimentary environment (i.e. back to the sediment-water interface). Incorporation of silt-clay grade material from the host sediment into burrow fills and/or linings creates only localized, discontinuous areas of reduced porosity and permeability (Figure 2.4), due to the silt-clay size fraction filling pore space. The removal of silt-clay grade material from the host sediment by deposit feeding organisms that defecate at the overlying sediment-water interface, can create areas of biologically enhanced porosity and permeability within burrows. Both of these biological processes generally improve the porosity and permeability characteristics of the sediment. The results are consistent with Meyer and Krause (2006) who documented higher and relatively isotropic directional permeabilities in bioturbated middle shoreface sandstones relative to un-bioturbated, laminated sandstones.

Our petrographic analyses demonstrate that the *Ophiomorpha*-producing organism(s) create localized zones of porosity reduction (along burrow walls), and the *Thalassinoides* tracemaker creates porosity enhancement, relative to the host sediment within the reservoir (Figures 2.2I-L). Corresponding spot-permeability measurements also display similar trends (Figures 2.4G-I).

2.5.2.1 Porosity and Permeability of Ophiomorpha-dominated Ichnofabric

This ichnofabric is dominated by conspicuous *Ophiomorpha* within burrow-mottled fine sandstones from the bioturbated fine sandstone facies (LF1). Samples 1, 2 and 3 are representative of the *Ophiomorpha*-dominated ichnofabric. The porosity estimate for Sample 1 is 20.3%, that of sample 2 is 27.2% and Sample 3 is 23.4% (Figure 2.2). Permeability ranges recorded from this facies range from 1.26 mD to 394.80 mD. The highest permeability values are from Sample 1 averaging 79.36 mD (Figure 2.4C), with Sample 2 and 3 averages of 9.32 mD and 18.33 mD, respectively (Figures 2.4F and 2.4I). Bioturbation level ranges from 60-100%, with discrete burrows including pellet-lined *Ophiomorpha* and the unlined tubular burrows of *Thalassinoides*. In addition, some undetermined sandstone-filled burrows and an inclined spreiten burrow are only visible in large thin slices (Figures 2.4G-I). Sandstone-rich zones are characterized by higher permeability zones (e.g., 8.84-394.80 mD; Figures 2.4C, 2.4F and 2.4I) than the mudstone-rich burrow-mottled zones (e.g., 1.26-66.86 mD; Figures 2.4F and 2.4I).

Ophiomorpha burrow fills, margins and linings have clay-rich pores, relative to the surrounding clean high-porosity sandstone. Permeability data support this observation, with spot permeability data points within *Ophiomorpha* and at the burrow margins being low (e.g., 1.54-15.71 mD), relative to the surrounding higher-permeability (e.g., 5.38-66.86 mD) sandstone (Figures 2.4I). In one of the studied specimens, oversized pores are present within *Ophiomorpha* burrow margins (Figures 2.2A-D). These are inferred to have formed by dissolution of burrow lining during diagenetic secondary porosity development (Hesse and Abid, 1988; Figure 2.4C). Thin section

samples were impregnated with blue epoxy prior to prepration to prevent clay disaggregation. *Ophiomorpha* were created by sediment-packing during deposit feeding activity, in which the trace making organism concentrates mud and organic-rich particles into burrow linings. The effect of this is to reduce porosity and permeability in the near-burrow environment relative to the biologically cleaned host sediment. The *Ophiomorpha* fill is a passive fill unrelated to the host sediment, which can locally even include ripple cross-lamination. In our material the burrow fill is typically of low permeability, though we acknowledge that this need not always be the case (Figures 2.4I and 2.5F).

Thalassinoides studied by us from L-55 are distinguishable as very thin mudstone-lined burrows, with fill similar to, or cleaner than, the enclosing matrix (Figures 2.2K and 2.2L). A halo of high-porosity, clean, well-sorted sandstone is present around a small number of *Thalassinoides*. For example, in sample 3 the *Thalassinoides* is 31.28 mD, the adjacent *Ophiomorpha* is 1.54-15.71 mD, and the mean permeability for the sample is 18.33 mD (Figures 2.4G-I). This burrow halo exhibits higher porosity and permeability than the matrix (Figure 2.4I), and may be the result of the trace-maker generating a current around its body and expelling fines into the water column (aquarium observations of modern *Neotrypaea californiensis* by McIlroy). At least in the Ben Nevis Formation core of well L-55, *Thalassinoides* is consistently associated with areas of enhanced porosity and permeability relative to the host sediment.

2.5.2.2 Porosity and Permeability of Ophiomorpha-Chondrites-Phycosiphon Ichnofabric

This ichnofabric is typically incompletely bioturbated (5-60% bioturbation). The sedimentary fabric is composed of bioturbated mudstone-rich laminae in a very fine-grained sandstone matrix (LF4). Pellet-lined *Ophiomorpha* and undetermined sandstone- and mudstone-filled traces are common. Samples 4 and 5 are representative of the *Ophiomorpha-Chondrites-Phycosiphon* ichnofabric. The porosity of sample 4 is estimated at 4.9% and that of sample 5 is 16.8% (Figure 2.3). This is significantly lower than the porosities of 20.3%, 27.2% and 23.4% from the sandstone-rich samples 1-3 (LF1; Figure 2.2). The permeability of samples in lithofacies 4 (LF4) range from 2.01 mD to 65.64 mD. Sample 4 has a mean permeability of 11.06 mD and Sample 5 a mean of 45.71 mD (Figures 2.5C and 2.5F).

Ophiomorpha and *Chondrites* within this ichnofabric are associated with zones of localized porosity and permeability reduction in their mudstone-rich burrow fills and linings (Figures 2.3 and 2.5). Pellet-lined and filled *Ophiomorpha* significantly reduce permeability (e.g., 2.01-8.96 mD; Figure 2.5C) relative to the host sediment (7.99-12.59 mD; Figure 2.5C). Large opaque zones associated with *Ophiomorpha* are pyritized organic-rich mudstone with low permeability values (e.g., 8.04-21.48 mD, Figure 2.5F) relative to the host sediment (e.g., 19.76-65.64 mD; Figure 2.5F). Widely spaced mudstone-filled *Chondrites* (1-2 mm diameter) do not affect permeability relative to host sediment (Figure 2.5F). At the microscopic-scale *Chondrites* significantly reduce porosity relative to the host sediment as silt-clay grade material is packed into pore space (Figures 2.3E-H).

Lamina-sets with sharp mud-rich drapes alternate with intervals showing diffuse lamination, interpreted to be formed by cryptobioturbation or liquefaction (Figure 2.5). Laminae adjacent to burrows are deflected by the vertical movements of bioturbating organisms (Figure 2.5B). Diffusely laminated lamina-sets are characterized by permeabilities between 5.89 mD and 33.60 mD, whereas inter-laminated massive sandstone intervals have permeabilities of 7.99-12.59 mD (Figure 2.5B and 2.5C).

2.5.2.3 Comparison of core plug and slab porosity and permeability

Core plug porosity values obtained for the sampled facies (LF1 and LF4) of the cored interval of Ben Nevis L-55 range from 9.2% to 22.7%, with an average value of 15.9% (Table 2.1, Core Laboratories Ltd., 1999). Visual porosity estimates of the 5 samples using the SimplePCI software on a blue epoxy impregnated thin section range from 4.9% to 27.2%, with an average value of 18.5% (Table 2.1). Micro-porosity is not measured in the 5 samples and is recorded as minor in the core plug analysis report (Core Laboratories Ltd., 1999). Core plug porosity data of given facies are thus in general agreement with porosity trends revealed in thin section and measurements.

Permeability values obtained for Ben Nevis L-55 core interval facies (LF1 and LF4) from the core plug data range from <1 mD to 376 mD with an average value of 44.9 mD (Table 2.1; Core Laboratories Ltd., 1999). Permeability data of the 5 samples using the probe-permeameter range from 1.5 mD to 394 mD, with an average value of 32 mD (Table 2.1). Spot-permeability data of bioturbated core slab samples reveals that that the mud-rich *Ophiomorpha* can locally reduce permeability by as much as approximately

33%, through incorporation and concentration of silt-clay grade material in burrow fill and lining (Figures 2.4 and 2.5). Conversely, sand-filled burrows such as *Thalassinoides* can enhance permeability by as much as 600%, through removal of silt-clay grade material from pore spaces (Figure 2.4). Although probe permeameter values correlate well with the corresponding core plug data, the collection of probe data at 1 cm intervals enables a more comprehensive understanding of the heterogeneous nature of the Ben Nevis L-55 core interval.

2.6 Porosity and permeability trends associated with bioturbation

Porosity and permeability in the Ben Nevis Formation of well L-55 are found to be controlled by a combination of sedimentary, biogenic and diagenetic processes. Clay and silt-rich laminae are associated with porosity and permeability reduction (Table 2.1). Bioturbation can either enhance or reduce permeability, depend on the burrow type and the behaviour of the trace-making organism in the Ben Nevis L-55 core interval.

Based upon our studies of bioturbation in the Ben Nevis Formation, we consider that the burrowing activity of animals can be grouped broadly into 5 categories with predictable effects on porosity and permeability:

1) "Sediment mixers" – cause indiscriminate mixing of sediment grains, decrease the isotropy or uniformity of the sediment by un-sorting any grain-size trends, and through mechanical destruction of laminae. Sediment mixers burrow in the sediment without sorting the sediment into distinct

burrow linings or fills. Clearly, the negative effect of diminished small-scale sorting is more than compensated for by the elimination of fine-grained laminae that act as baffles. For example burrow-mottled (Figure 2.4) and diffuse to massive textures (Figure 2.5) create intense to complete levels of bioturbation (>90%) with the net-effect of permeability enhancement (e.g., diffuse laminae, 5.89-33.60 mD and inter-laminated sandstone, 7.99-12.59 mD; Figures 2.5B and 2.5C).

2) "Sediment cleaners" – increase isotropy of the sediment by selectively removing fine-grained material (e.g., pore-filling clay-silt and organic matter) from the sediment by ingestion and subsequent defecation of fines into the water column or creating a current within the near-burrow environment. Burrows consisting of well-sorted clean sandstone fill, relative to enclosing host sediment, are considered to be produced by sediment cleaning organisms with the net-effect of permeability enhancement (e.g., *Thalassinoides* burrow margin is 31.28 mD, the adjacent *Ophiomorpha* burrow fill is 1.54-15.71 mD, and the mean permeability for the sample is 18.33 mD; Figure 2.4I). *Thalassinoides* traces with clean sandstone halos could be categorized as sediment cleaners (Figures 2.2I-L and 2.4G-I).

3) "Sediment packers" – incorporate finer grained material (e.g., clay and fine organic matter) from the host sediment into burrow fills and/or linings decreases isotropy of the sediment. Packing of the clay-silt size fraction into pore space by organisms locally reduces permeabilities (e.g., *Ophiomorpha* burrow permeability is 1.54-15.71 mD, relative to 5.38-66.86 mD of the

surrounding higher-permeability sandstone; Figure 2.4I). Burrows of *Ophiomorpha*, *Chondrites*, *Phycosiphon*, *Asterosoma* and *Teichichnus* can be categorized as "sediment packers" (Figures 2.3E-H; 2.4E, 2.4I; 2.5, and 2.6).

4) Combination "Sediment cleaners and packers" – overall decrease isotropy of the sediment. These organisms pack mud into a mud-filled core and clean adjacent sediment creating a coarser grained halo. *Phycosiphon* burrows are an excellent example of this combined behaviour (Figure 2.6G).

5) "Pipe-work builders" –open semi-permanent burrows in sediment perforate pre-existing physical sedimentary fabrics. Such burrows are horizontal galleries connected at depth by vertical pipes to the sediment-water interface. Upon burrow abandonment, the burrow generally remains open and is passively filled with the overlying sediment at the sediment-water interface.

    a. If the "pipe-work" is filled with sand grade material, high-porosity biogenic macro-pore networks can result. If such burrows are of sufficiently high density, effective permeability at the bed-scale can be greatly improved. Bioturbation-enhanced porosity and permeability has been documented in a number of settings associated with sandstone-filled burrows into mudstone horizons including *Glossifungites* ichnofacies (Weber, 1982; Gingras *et al.*, 1999). This study includes examples of enhanced permeability in association with

Thalassinoides from sandstone reservoir of the Ben Nevis Formation (Figures 2.4G-I).

b. If the "pipe network is filled with mudstone, the effect is generally a decrease in net-to-gross sandstone ratio, but without serious deleterious effect on host sediment reservoir properties.

2.7 Conclusions

The burrowing activity of marine organisms produces a variety of burrows, tracks and trails, reworking lithic clasts, mineral grains and organic matter to modify primary physical sedimentary fabrics. The action of bioturbators can be classified as sediment mixing, sediment cleaning, sediment packing and pipe-work building strategies. Bioturbation has the potential to either increase isotropy by un-sorting hydrodynamically-sorted grains or decrease isotropy by sorting grains, and through creation of open burrow systems.

In this sandstone-dominated reservoir, *Ophiomorpha* are the most conspicuous element of the ichnofauna throughout the well, and are characteristic of several net-pay intervals. Although our research demonstrates the conspicuous *Ophiomorpha* reduce porosity and permeability, the subtle sand-filled burrows of *Thalassinoides* are recognized as enhancing petrophysical properties in the net-pay intervals.

Ophiomorpha in the Ben Nevis Formation of well L-55 display "sediment packing" behaviour in which clay-silt grade material is removed from the sediment, and

incorporated into burrow linings and fill, thereby markedly reducing porosity and permeability (e.g., 33%). *Thalassinoides*, the other key trace fossil is classified as a "sediment cleaner" and "pipe-work builder" increases isotropy and is related to enhanced porosity and permeability (up to 600% greater than the host sediment). Burrow-mottling, diffuse laminae and massive intervals un-sort the primary sedimentary fabrics formed during deposition. In intensely bioturbated lithologies bioturbation has the net-effect of permeability enhancement.

The implication of animal-sediment interactions, for example the porosity and permeability reducing sediment packing activity within the *Ophiomorpha*-dominated ichnofabric, and porosity and permeability enhancing sediment cleaning activity within the *Ophiomorpha-Chondrites-Phycosiphon* ichnofabrics are easily identified in core, and are hence of predictive value. Assignment of the aforementioned 5 categories of burrowing activity can be applied to other core analyses and used as a tool to predict effects on porosity and permeability.

References

Aigner, T., 1985, Storm depositional systems; dynamic stratigraphy in modern and ancient shallow-marine sequences: Berlin, Springer-Verlag, 174pp.

Bentley, S. J., and A. Sheremet, 2003, New model for the emplacement, bioturbation, and preservation of fine-scaled sedimentary strata: Geology, v. 31, p. 725-728.

Brettle, M. J., D. McIlroy, T. Elliott, S.J. Davies, and C.N. Waters, 2002, Identifying cryptic tidal influences within deltaic successions; an example from the Marsdenian (Namurian) interval of the Pennine Basin, UK: Journal of the Geological Society of London, v. 159, p. 379-391.

Bromley, R.G., and A.A. Ekdale, 1984, *Chondrites*: a trace fossil indicator of anoxia in sediments: Science, v. 224, p. 872-874.

Bromley, R.G., and A.A. Ekdale, 1986, Composite ichnofabrics and tiering of burrows: Geological Magazine, v. 123, p. 59-65.

Bromley, R.G., and G.K. Pedersen, 2008, *Ophiomorpha irregulaire*, Mesozoic trace fossil that is either well understood but rare in outcrop or poorly understood but common in core: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270, p. 295-298.

Bromley, R.G., 1990, Trace fossils: biology and taphonomy: London, Unwin Hyman, 280 pp.

Canada-Newfoundland and Labrador Offshore Petroleum Board, 2008, Annual Report 2007/2008, 52 pp.

Cannon, S.J.C., and S. Gowland, 1996, Facies controls on reservoir quality in the Late Jurassic Fulmar Formation, Quadrant 21, UKCS, *in* A. Hurst, H.D. Johnson, S.D. Burley, A.C. Canham, and D.S. Mackertich, eds., Geology of the Humber Group: Central Graben and Moray Firth, UKCS: Geological Society (London) Special Publication 114, p. 215-233.

Core Laboratories Canada Ltd., 1999, Core analysis report for Jeanne d'Arc Basin operations: Chevron et al Ben Nevis L-55, Ben Nevis, Newfoundland, No. 52143-99-9031, 28 pp.

Crerar, E.E., and R.W.C. Arnott, 2007, Facies distribution and stratigraphic architecture of the Lower Cretaceous McMurray Formation, Lewis Property, northeastern Alberta: Bulletin of Canadian Petroleum Geology, v. 55, p. 99-124.

Cunningham, K. J., M. C. Sukop, H. Huang, P. F. Alvarez, H. A. Curran, R. A. Renken, and J. F. Dixon, 2009, Prominence of ichnologically influenced macroporosity in the karst Biscayne Aquifer: stratiform "super-K" zones: Geological Society of America Bulletin, v. 121, p. 164-180.

von der Dick, H., 1989, Environment of petroleum source rock deposition in the Jeanne d'Arc Basin off Newfoundland, *in* A. J. Tankard and H. R. Balkwill, eds., Extensional tectonics and stratigraphy of the North Atlantic margins: AAPG Memoir 46, p. 295-303.

Dreyer, T., A. Scheie, and O. Walderhaug, 1990, Minipermeameter-based study of permeability trends in channel sand bodies: AAPG Bulletin, v. 74, p. 359-374.

Driscoll, N.W., J.R. Hogg, N. Christie-Blick, and G.D. Karner, 1995, Extensional tectonics in the Jeanne d'Arc Basin, offshore Newfoundland: implications for the

timing of break-up between Grand Banks and Iberia, *in* R.A. Scrutton, M.S. Stoker, G.B. Shimmield, and A.W. Tudhope, eds., The tectonics, sedimentation and palaeoceanography of the North Atlantic region: Geological Society (London) Special Publication 90, p. 1-28.

Dumas, S. and R.W.C. Arnott, 2006, Origin of hummocky and swaley cross-stratification: the controlling influence of unidirectional current strength and aggradation rate: Geology, v. 34, p. 1073-1076.

Einsele, G., and A. Seilacher, 1991, Distribution of tempestites and turbidites, *in* G. Einsele, W. Ricken, and A. Seilacher, eds., Cycles and events in stratigraphy: Berlin, Springer-Verlag, p. 377-382.

Ekdale, A.A., R.G. Bromley, and S.G. Pemberton, 1984, Ichnology: the use of trace fossils in sedimentology and stratigraphy: SEPM Short Course Notes 15, 317 p.

Follmi, K.B., and K.A. Grimm, 1990, Doomed pioneers: Gravity-flow deposition and bioturbation in oxygen-deficient environments: Geology, v. 18, p. 1069-1072.

Frey, R.W., J.D. Howard, and W.A. Pryor, 1978, *Ophiomorpha*: its morphologic, taxonomic, and environmental significance: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 23, p. 199-229.

Garton, M., and D. McIlroy, 2006, Large thin slicing: a new method for the study of fabrics in lithified sediments: Journal of Sedimentary Research, v. 76, p. 1252-1256.

Gingras, M.K., S.G. Pemberton, C.A. Mendoza, and F. Henk, 1999, Assessing the anisotropic permeability of *Glossifungites* surfaces: Petroleum Geoscience, v. 5, p. 349-357.

Gingras, M.K., G.S. Pemberton, F. Henk, J.A. MacEachern, C.A. Mendoza, B. Rostron, R. O'Hare, and M.V. Spila, 2007, Applications of ichnology to fluid and gas production in hydrocarbon reservoirs, *in* J.A. MacEachern, K.L. Bann, M.K. Gingras, and G.S. Pemberton, eds., Applied Ichnology: SEPM Short Course Notes 52, p. 131-145.

Goggin, D.J., R.L. Thrasher, and L.W. Lake, 1988, A theoretical and experimental analysis of minipermeameter response including gas slippage and high velocity flow effects: In Situ, v. 12, p. 79–116.

Herringshaw, L.G., O. Sherwood, and D. McIlroy, 2010, Ecosystem engineering by bioturbating polychaetes in event bed microcosms: Palaios, v. 25, p. 46-58.

Hesse, R., and I.A. Abid, 1998, Carbonate cementation: the key to reservoir properties of four sandstone levels (Cretaceous) in the Hibernia Oilfield, Jeanne d'Arc Basin, Newfoundland, Canada, *in* S. Morad, ed., Carbonate cementation in sandstones: distribution patterns and geochemical evolution: Special Publication of the International Association of Sedimentologists 26, p. 363-393.

Hildebrandt, C., and S. Egenhoff, 2007, Shallow-marine massive sandstone sheets as indicators of palaeoseismic liquefaction; an example from the Ordovician shelf of central Bolivia: Sedimentary Geology, v. 202, p. 581-595.

Howard, J.D., 1972, Trace fossils as criteria for recognizing shorelines in stratigraphic record; Recognition of ancient sedimentary environments, *in* W.K. Hamblin, ed., Recognition of Ancient Sedimentary Envorironments: SEPM Special Publication 16, p. 215-225.Howard, J.D., and R.W. Frey, 1975, Regional animal-sediment characteristics of Georgia Estuaries: Senckenbergiana Maritima, v. 7, p. 33-103.

Hubbard, R.J., J. Pape, and D.G. Roberts, 1985, Depositional sequence mapping as a technique to establish tectonic and stratigraphic framework and evaluate hydrocarbon potential on a passive continental margin, *in* O.R. Berg, and D.G. Woolverton, eds., Seismic stratigraphy II: an integrated approach to hydrocarbon exploration: AAPG Memoir 39, p. 79-91.

Jerram, D.A., 2001, Visual comparators for degree of grain-size sorting in two and three-dimensions: Computers & Geoscience, v.27, p. 485-492.

Martin, M.A., and J.E. Pollard, 1996, The role of trace fossil (ichnofabric) analysis in the development of depositional models for the Upper Jurassic Fulmar Formation of the Kittiwake Field (Quadrant 21 UKCS), *in* A. Hurst, H.D. Johnson, S.D. Burley, A. C. Canham, and D. S. Mackertich, eds., Geology of the Humber Group: Central Graben and Moray Firth, UKCS: Geological Society (London) Special Publication 114, p. 163-183.

McAlpine, K.D., 1990, Mesozoic stratigraphy, sedimentary evolution, and petroleum potential of the Jeanne d'Arc Basin, Grand Banks of Newfoundland: Geological Survey of Canada, v. 89-17, p. 50.

McIlroy, D., 2004, Ichnofabrics and sedimentary facies of a tide-dominated delta; Jurassic Ile Formation of Kristin Field, Haltenbanken, offshore mid-Norway, *in* D. McIlroy, ed., The application of ichnology to palaeoenvironmental and stratigraphic analysis: Geological Society (London) Special Publication 228, p. 237-272.

McIlroy, D., 2007, Lateral variability in shallow marine ichnofabrics: implications for the ichnofabric analysis method: Journal of the Geological Society of London, v. 164, p. 359-369.

Meyer, R., and F.F. Krause, 2006, Permeability anisotropy and heterogeneity of a sandstone reservoir analogue: An estuarine to shoreface depositional system in the Virgelle Member, Milk River Formation, Writing-on-Stone Provincial Park, southern Alberta: Bulletin of Canadian Petroleum Geology, v. 54, p. 301-318.

Miller, M.F., and H.A. Curran, 2001, Behavioral plasticity of modern and Cenozoic burrowing thalassinidean shrimp: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 166, p. 219-236.

Owen, G., 1996, Experimental soft-sediment deformation; structures formed by the liquefaction of unconsolidated sands and some ancient examples: Sedimentology, v. 43, p. 279-293.

Pemberton, S.G., M. Spila, A.J. Pulham, T. Saunders, J.A. MacEachern, D. Robbins, and I.K. Sinclair, 2001, Ichnology and sedimentology of shallow to marginal marine systems: Ben Nevis and Avalon reservoirs, Jeanne d'Arc Basin: Geological Association of Canada, Short Course Notes 15, 343 pp.

Pemberton, S.G., and M.K. Gingras, 2005, Classification and characterizations of biogenically enhanced permeability: AAPG Bulletin, v. 89, p. 1493-1517.

Pryor, W.A., 1975, Biogenic sedimentation and alteration of argillaceous sediments in shallow marine environments: Geological Society of America Bulletin, v. 86, p. 1244-1254.

Richards, P.C., 1992, An introduction to the Brent Group: a literature review, *in* A. C. Morton, R.S. Haszeldine, M.R. Giles, and S. Brown, eds., Geology of the Brent Group: Geological Society (London) Special Publication 61, p. 15-26.

Sheehan, P.M., and D.R.J. Schiefelbein, 1984, The trace fossil *Thalassinoides* from the Upper Ordovician of the eastern Great Basin: deep burrowing in the early Paleozoic: Journal of Paleontology, v. 58, p. 440-447.

Sinclair, I.K., 1988, Evolution of Mesozoic-Cenozoic sedimentary basins in the Grand Banks area of Newfoundland and comparison with Falvey's (1974) rift model: Bulletin of Canadian Petroleum Geology, v. 36, p. 255-273.

Sinclair, I.K., 1993, Tectonism: the dominant factor in mid-Cretaceous deposition in the Jeanne d'Arc Basin, Grand Banks: Marine and Petroleum Geology, v. 10, p. 530-549.

Spila, M.V., S.G. Pemberton, B. Rostron and M.K. Gingras, 2007, Biogenic textural heterogeneity, fluid flow and hydrocarbon production: bioturbated facies Ben Nevis Formation, Hibernia Field, Offshore Newfoundland, in J.A. MacEachern, K.L. Bann, M.K. Gingras, and G.S. Pemberton, eds., Applied Ichnology: SEPM Short Course Notes 52, p. 363-380.

Swinbanks, D.D., and J.L. Luternauer, 1987, Burrow distribution of thalassinidean shrimp on a Fraser Delta tidal flat, British Columbia: Journal of Paleontology, v. 61, p. 315-332.

Tankard, A.J., and H.J. Welsink, 1987, Extensional tectonics and stratigraphy of Hibernia oil field, Grand Banks, Newfoundland: AAPG Bulletin, v. 71, p. 1210-1232.

Tankard, A.J., H.J. Welsink and W.A.M. Jenkins, 1989, Structural styles and stratigraphy of the Jeanne d'Arc Basin, Grand Banks of Newfoundland, *in* A.J Tankard, and H.R. Balkwill, eds., Extensional tectonics and stratigraphy of the North Atlantic margins: AAPG Memoir 46, p. 175-195.

Taylor, A.M., and R. Goldring, 1993, Description and analysis of bioturbation and ichnofabric: Journal of the Geological Society, London, v. 150, p. 141-148.

Taylor, A.M., R. Goldring, and S. Gowland, 2003, Analysis and application of ichnofabrics: Earth-Science Reviews, v. 60, p. 227-259.

Weber, K.J., 1982, Influence of common sedimentary structures on fluid flow in reservoir models: Journal of Petroleum Technology, v. 34, p. 665-672.

Wetzel, A., and R.G. Bromley, 1994, Phycosiphon incertum revisited: *Anconichnus horizontalis* is its junior subjective synonym: Journal of Paleontology, v. 68, p. 1396-1402.

Wheatcroft, R.A., 1990, Preservation potential of sedimentary event layers: Geology, v. 18, p. 843-845.

Chapter 3: Lateral trends in the ichnological variability of shallow marine successions

Abstract

High resolution paleoenvironmental reconstruction in marine systems can be constrained by understanding variability, and trends in the distribution of benthic organisms. Spatial distribution of trace fossils is complex, and involves both biological and physico-chemical parameters. Superimposed upon these ecological/paleoenvironmental signatures, are the effects of burrow preservation (taphonomy). Ichnofabric and ichnofacies seldom preserve trace fossils relating to a single benthic community, or colonization surface. On biological timescales ichnological assemblages are commonly the product of several time-averaged communities, or a condensed representation of an unknown number of communities with hiatuses. Three siliciclastic shallow marine along-strike profiles were studied from the Quaternary Conway Flat, New Zealand; Late Cretaceous Neslen Formation, Utah, USA; and Neogene Pohutu Formation, East Cape. Maximum ichnological variability was found in the shelfal deposits of the Pohutu Formation, characterized by slow continuous deposition in association with event bed deposition. Neslen Formation shoreface and Conway lower delta plain studies were characterized by relative little lateral change in ichnofabric. Along-strike variability, or patchiness, was found to be un-related to proximity to the paleo-shoreline in the three wave-dominated depositional systems. Instead, the most

critical factor appears to be the sediment accumulation style. Slow continuous deposition is found to produce complex, and highly patchy ichnofabrics, whereas rapid, episodic, event bed deposition was found to be associated with the most uniform development of ichnofabric. There is lateral ichnological variability within most beds but modes of feeding/bioturbation are commonly more uniform than ichnogeneric distributions. Where feeding strategies/bioturbation styles are the same, the net effect on reservoir quality is seen to be less variable than would first appear.

3.1 Introduction

Some of the world's most productive petroleum reservoirs are highly bioturbated, with biogenic structures being integral to facies analysis, and controlling reservoir quality (e.g., Martin and Pollard, 1996). Effective production of hydrocarbon reservoirs requires reliable prediction of facies-related reservoir properties, and correlation at the inter-well scale. It is also becoming clear that reservoir quality, can be significantly impacted by bioturbation (Gingras *et al.*, 1999, 2002, 2004; Pemberton and Gingras, 2005; Tonkin *et al.*, 2010). Studies of bioturbation are conventionally aimed at understanding stratigraphic changes in ichnology to determine facies trends at the bedset scale, usually within progradational packages (parasequences and parasequence sets, Van Wagoner et *al.*, 1990). In effect, such studies provide information about down-depositional-dip ichnological trends (by application of Walther's Law; Middleton, 1973), and are based on both semi-quantitative and qualitative approaches (McIlroy *et al.*, 2004; MacEachern *et al.*, 2007). Implicit to this is the assumption that ichnofabrics only vary in a down-dip

direction, as seen in bed-by-bed changes in ichnology (Taylor *et al.*, 2003). Recent study of ichnofabrics, from within a single bed, have revealed significant local patchiness in ichnofabric that requires reassessment of the assumption of ichnological homogeneity at the bed scale (McIlroy, 2007).

3.1.1 Patchiness of the modern endobenthos

Study of spatial variability in modern benthic populations by biologists has categorized benthic seafloor patchiness as being in the form of gradients, clusters, and mosaics:

1) Gradient patterns are comparable to the inferred along-depositional-dip variability inherent in most ichnological studies in the rock record. Species are distributed along environmental gradients, and variability is gradual along the gradient (e.g. onshore to offshore), and reflects trends in sedimentological parameters (e.g. energy and grain size; Johnson, 1971; Bloom *et al.*, 1972; Valentine and Jablonski, 2010).

2) Clustering and clumping patterns of species, or communities constitute abrupt or discontinuous spatial distributions, and are often recognized as discrete, intensely populated, patches on the seafloor (Woodin, 1976; Tilman *et al.*, 1997).

3) Mosaic patterns have spatial-temporal significance, clusters of species or communities overlap, and undergo disturbances over time. Both physically-induced (e.g. erosion and detrital inputs), and biologically-induced (e.g. predation and larval dispersal) phenomena can produce a complex spatial patchwork on the seafloor. When the time interval between disturbance events is non-uniform, this can add a temporal component

to mosaic ecological trends/patterns of communities (Johnson, 1970; Reise, 1979; Levinton and Kelaher, 2004).

Clustering and mosaic patterns are common phenomena in response to local trends, usually parallel to the shoreline, and are typically not systematically related to depth gradient patterns. The most common first-order biological controls on patchiness of the modern seafloor are: 1) localized input of particulate food to the sediment-water-interface (Shanks, 2002), which creates heterogeneity in the distribution of food resources; and 2) the motility and mobility of benthic organisms, which greatly affects their ability to exploit spatially-localized resources (Levinton and Kelaher, 2004), particulary after defaunation events. The spatio-temporal controls acting on the distribution of modern benthic seafloor communities are complex. Anomalously large detrital input events may attract larvae or boost invertebrate population growth (Levinton and Kelaher, 2004). The motility of epibenthic, and endobenthic organisms encompasses both adult, and juvenile organisms. The mobility of organisms mostly affects juveniles, and is caused by currents (e.g. Thorson, 1950; Beukema and Vlas, 1989).

Seafloor patchiness is widely studied, by both biologists and ecologists. However, equating such ecological/biological variability with ichnofabrics in the rock record is not straightforward. Biological studies are typically focused on organisms, rather than their burrows, and snapshots of ecology are on biological rather than geological timescales. Inherent in any analysis of ancient ecosystems is the possibility for time averaging of skeletal assemblages, by reworking and winnowing of skeletal material (Kidwell and Bosence, 1991; Valentine and Jablonski, 1993; Fürsich and Aberhan, 1994). Superimposed on these ecological/paleoenvironmental parameters are

taphonomic processes. It is almost impossible to determine whether an assemblage of fossils or trace fossils reflects a true biological community or ichnocoenosis (Cummins *et al.*, 1986; Kidwell and Flessa, 1996; McIlroy and Garton, 2010; Liu *et al.*, 2011).

There is a need to develop an understanding of the combined effects of biological patchiness with respect to the time-averaging typical of ancient sedimentary units when interpreting ichnology. The variability seen in ichnofabrics is pertinent to: 1) the establishment of ichnologically-defined facies (McIlroy, 2008); 2) interpreting paleoenvironmental parameters from ichnofossil assemblages (Taylor *et al.*, 2003); and 3) predicting changes in sediment properties in porous media (Tonkin *et al.*, 2010, Pemberton and Gingras, 2005).

3.1.2 Paleoecological studies of patchiness in ancient strata

A bioturbated bed or ichnofabric rarely preserves burrows relating to a single benthic community. Ichnofabrics are commonly the product of several time-averaged communities. Therefore a lateral profile along a bioturbated bed will commonly incorporate both spatial, and temporal components. There are few studies of lateral variability of trace fossils/ichnofabrics/ichnofacies (McIlroy, 2007). Given the expected hydrodynamic homogeneity on the scale of tens of meters, much of the variability in ichnofabric is likely to be primarily related to time-averaged patchiness (McIlroy, 2007).

When sampling for patchiness on the modern seafloor, and in the rock record a consistent methodology is important, small replicate sampling protocol is recommended (Bennington, 2003), although time-averaging on a ecological timescale (e.g. seasonal, Gingras *et al.*, 2008) may be effective in homogenizing patchiness. If burrow type is

equated with trophic mode, the effects of time averaging can be incorporated into understanding of lateral variability in ichnofabrics. Ichnofabrics could be considered as being representative of in situ spatial variability, the ichnological distribution being the result of the life activity on the ancient sea-floor. Cross-cutting relationships, and depth of burrowing seen in ichnofabrics additionally provide proxies for community structure, and succession can be considered with respect to sediment accumulation style.

This chapter expands on McIlroy (2007), and considers ichnological variability in three case studies from a range of onshore to offshore shallow marine settings. The aim of the presented studies is to determine the lateral variability of ichnological, and sedimentological characteristics of a given bed along a horizontal transect within a range of wave-influenced depositional settings. This understanding of the variability of ichnofabrics is fundamental to reliable understanding of what constitutes a significant (interpretable) difference in ichnofabrics relative to normal inherent variability (McIlroy, 2007). Comparable ichnological datasets have been collected from three case studies from onshore to offshore: 1) a proximal Quaternary fan delta succession (New Zealand); 2) a Cretaceous shoreface succession (Utah); and 3) a Miocene offshore shelfal succession (New Zealand). Collection of semi-quantitative and qualitative ichnological data such as bioturbation intensity, ichnotaxa identification, burrow size/fill, cross-cutting relationships, and bioturbation styles highlights ichnofaunal response to changes in physico-chemical parameters, and enables recognition of trends in spatial distribution. These case studies are used to assess the importance of lateral ichnological variability in a number of wave-dominated shallow marine facies.

3.2 Methodology

To aid paleoenvironmental reconstruction of each case study, a variety of techniques are used to interpret the complex relationship between physico-chemical parameters and the associated ichnology. Well-exposed, accessible, laterally-continuous outcrops were logged to determine sedimentary facies. At intervals along a chosen bedding plane sedimentological and ichnological observations were made to assess lateral variability along 35 m to 60 m profiles.

3.2.1 Ichnological analysis

Each sample was characterized using both the ichnofabric and the ichnofacies approaches (see Chapter 1). Each sample underwent detailed ichnological analysis. Ichnofabric analysis involves categorization of the ichnology, ichnodiversity, burrow diameter, bioturbation intensity and cross cutting relationships (Taylor and Goldring, 1993; Taylor *et al.*, 2003). Semi-quantitative data on bioturbation intensity was based on the amount of destruction of sedimentary fabric by bioturbation (Bioturbation Index or BI; Taylor and Goldring, 1993).

Assessment of ichnodiversity involved quantification of the burrow number of ichnotaxa present, and is somewhat subjective due to taphonomic and ichnotaxonomic biases. Potential taphonomic biases include preferential preservation of mid- to deep-tier level trace fossils, late colonizers, deposit feeding burrows, and large burrows ('elite traces' of Bromley, 1996). Other taphonomic controls include: 1) the degree of lithological heterogeneity and intensity of bioturbation; and 2) difficulties of identifying

ichnotaxa from vertical cross-sections (e.g. McIlroy *et al.*, 2009). Maximum burrow diameter was measured from all the most abundant ichnotaxa. This quantification of burrow size was performed for the total abundance number of trace fossils in each ichnofabric. Burrow diameter has been used as a proxy to define fluctuating bottom water oxygenation (cf. Bromley and Ekdale, 1984), although preservation biases (taphonomy), and the potential to sample a range of both juveniles and adult trace-making organisms is potentially misleading. In this work, ichnofabrics were categorized and named based on the dominant trace fossil or fossils within a sample or sample area (Taylor *et al.*, 2003; McIlroy, 2004, 2007, 2008).

Ichnofacies were determined through comparison of the ichnotaxa composition of assemblages to pre-established/archetypal ichnofacies according to the proposals of MacEachern *et al.* (2010). Burrowing activity categories or bioturbation styles (Tonkin *et al.*, 2010) are applied to each dataset studied, in order to describe the physical modifications made by each ichnotaxon or "bioturbation style" (Table 3.1). The categories of bioturbation styles used are: sediment mixers, sediment cleaners, sediment packers and pipe-work builders (Chapter 2; Tonkin *et al.*, 2010). This new classification can be used to summarize ichnological patterns, and can be used for reservoir characterization.

The primary objective for data collection was to undertake systematic sampling (e.g. replicate sampling; Bennington, 2003) as a basis for a quantitative ichnological study. The following data were collected at 5 m or 10 m lateral spacings along horizontal transects in the field or analyzed from slab faces:

1) Grain size.

2) Lithology.

3) Organic matter content.

4) Body fossil identification and abundance.

5) Sedimentary structures.

6) Diagenetic features.

7) Bed thickness.

8) Intensity of bioturbation.

9) Ichnotaxon identification and abundance.

10) Burrow size.

11) Burrow fill.

12) Depth of bioturbation.

13) Cross cutting relationships between trace fossils.

14) Ichnodiversity.

These data are used to systematically assess the relative sedimentological and ichnological heterogeneity across a lateral profile (see reviews in Taylor *et al.*, 2003; McIlroy, 2004 for detailed methodology). This ichnological approach is used to decipher a high resolution depositional history from each lateral profile and highlights along-strike ichnological variability. Biogenic structures that cannot be attributed to a specific ichnotaxon (for lack of appropriate ichnotaxobases) are recorded, and are considered an important component of ichnological analyses. Burrow-mottling textures and cryptobioturbation are the net effect of bulk sediment mixing tracemaker behaviours, and in the case studies presented herin constituent a significant of the ichnofabric. It is

important to document these structures since they are a component of the ichnofabric, and can affect bulk sediment properties (e.g. Chapter 2, Tonkin *et al.*, 2010).

Slab face analyses, analogous to core used in hydrocarbon exploration, enable core-width (40-100 mm) views of sedimentary environment and ichnofabric. Thin slabs of sedimentary rock were sampled at 5 or 10 m spacings along a horizontal transect, to assess variability over lateral distances of up to 60 m. In the Quaternary case study, collection of samples was not possible and vertical surfaces (0.4 m by 0.4 m) on outcrop surfaces were cut into the cliff face (with a blade) and detailed descriptions and photography were collected. While lateral transects of the scale of 100s of meters would be ideal, no suitably accessible beds were located at the field localities. Samples have undergone facies, ichnological, petrographic analysis, and large thin slicing (Garton and McIlroy, 2006).

3.2.2 Thin section analysis

Thin sections (25 mm by 45 mm) were cut from a slice of the sample slab face. Detailed petrographic analysis of each thin section are undertaken, including description of: grain size, sorting, roundness of grains, grain shape, matrix distribution, mineralogy, and cementation. Visual estimates of sorting were measured using comparison charts (Jerram, 2001). Proportions of quartz, calcite, clay and organic matter were visually estimated and photomicrographs were taken of microfabric textures for each sample. Petrographic analysis provides microscopic detail, which aids lithological classification and enables identification of mineralogical burrow-grain relationships.

3.2.3 Large Thin Slicing

The technique of large thin slicing is used to study the sedimentary and biogenic fabrics in sandstone and mudstone lithologies in transmitted light (Garton and McIlroy, 2006). When viewed in transmitted light, the large thin slices display sedimentary structures and the ichnology not otherwise visible in polished hand specimen or field samples.

The results of three case studies were chosen to reflect a range of onshore to offshore facies across wave-influenced shallow marine systems: 1) a Quaternary lower delta plain in a fan delta succession (New Zealand); 2) a Cretaceous shoreface succession (Utah); and 3) a Miocene offshore shelfal succession (New Zealand).

3.3 Proximal fan delta succession (Quaternary Conway Flat, NZ)

Coarse-grained fan delta deposits are well-exposed in coastal cliffs at Conway Flat, South Island, New Zealand (Figure 3.1). This Quaternary succession is composed of a complex of fan-delta facies including pro-fan-delta, gravelly distributary channels, sandy gravel barrier bars and embayment facies (Lewis and Ekdale, 1991). The lateral profile is measured within the delta front-delta plain transition facies association (Lewis and Ekdale, 1991).

In the late Quaternary, a series of small, short, and steep fan deltas drained the Hawkeswood Range, building into the nearby Pacific Ocean (Figure 3.1). The gravel of the Gilbert-type fan deltas was sourced from the Mesozoic sandstones of the Hawkeswood Range (Rattenbury *et al.*, 2006). Loess-rich sediment was derived from the

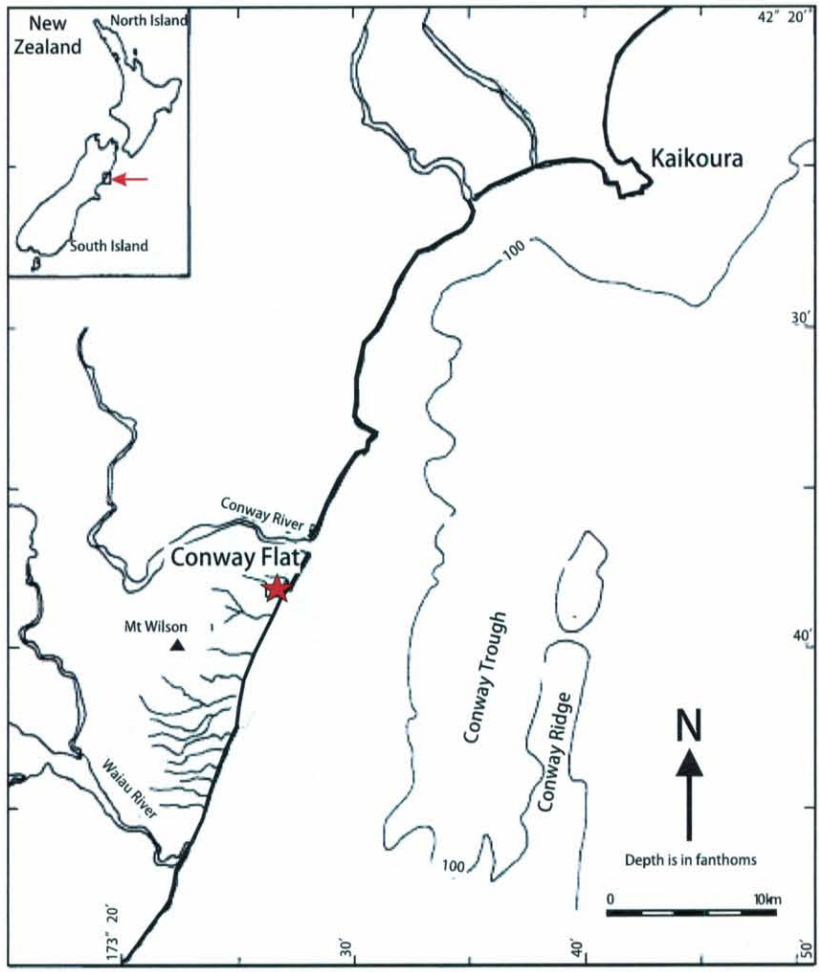


Figure 3.1. Locality map of Conway Flat, South Island, New Zealand. Cliff sections of Quaternary age sand, mud and gravel are exposed parallel to modern day Conway coastline. The Hawkeswood Range trend NE-SW through Mt Wilson (elevation 640 m). Offshore from the field locality lies the Conway Trough and Ridge in the SW Pacific Ocean (taken from Lewis and Ekdale, 1991). The 30m length lateral profile was sampled from a coastal cliff section.

Southern Alps as a product of wind deflation from glacial outwash plains, and fluvial transport (Lewis and Ekdale, 1991; McConnico and Bassett, 2007). The bathymetrically deep (>800 m) Conway Trough lies just offshore and runs parallel to the present day coastline, and is the receiving basin for coarse-grained deltaic sediments (Carter *et al.*, 1982; Figure 3.1). In the most northern part of the fan delta complex exposed along the Conway Flat coastline, fossil wood has been ^{14}C dated at between 7600 and 8400 years (Ota *et al.*, 1984). The sedimentation rate is calculated at 0.5 m ($1000yr^{-1}$) since 20,000 yr BP (Carter *et al.*, 1982).

Facies architecture in the fan delta is highly complex and laterally variable. A 25 m high cliff section within the embayment facies (Lewis and Ekdale, 1991) was logged. The lateral profile bed is part of the distal embayment facies characterized by moderately to intensely bioturbated (BI 3 to BI 5, Figures 3.2 and 3.3) sand, inter-bedded with very thin carbonaceous mud and silt to very fine sand-grade loess deposits. The horizon chosen for the lateral profile study is at the proximal delta front-lower delta plain transition lies stratigraphically above a delta front, gravelly bar facies, and below a delta plain, rhizolith-dominated mud facies. Hand samples were not collected along the profile due to the unconsolidated nature of the Quaternary sediments, a small thin section sized sample was collected intact. Instead, a smooth 0.4 m by 0.4 m area was prepared in the field. A lateral profile of 30 m was logged at 5 m intervals (Figures 3.2, 3.3 and 3.4). The short length of the lateral profile and closer interval spacing highlights the lack of continuity of beds within this embayment facies.

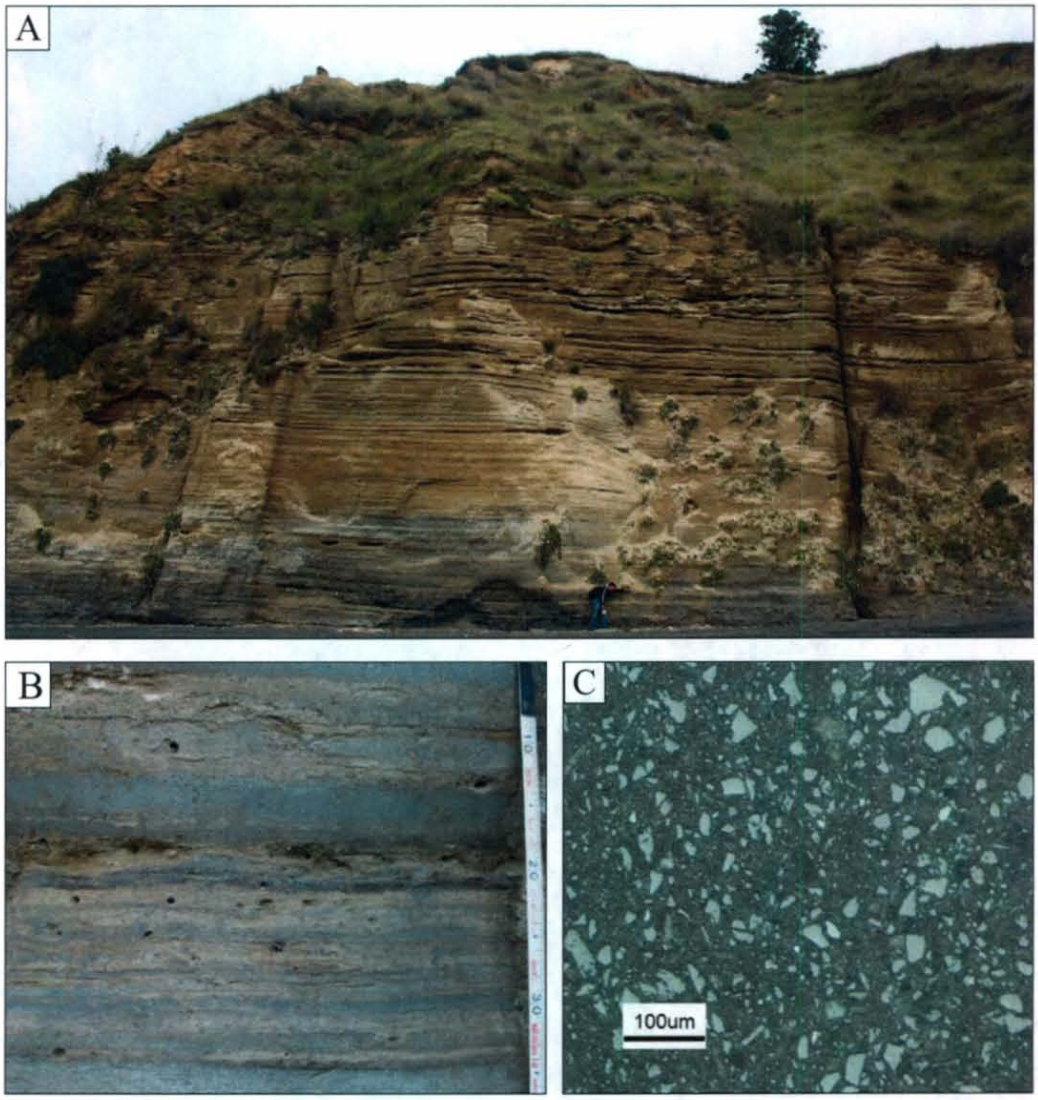


Figure 3.2. Quarternary proximal fan delta plain facies, Conway Flat, New Zealand. **A)** Along-strike view of lateral profile bed north of Ploughmans Creek, Conway Flats, North Canterbury, New Zealand. **B)** Slab sample C3 at 10m, 0.4m by 0.4m quadrat area containing mudstone with very thin interbeds of carbonaceous mud, silt, and cross-laminted very fine sand. **C)** Photomicrograph of thin section from proximal delta plain facies.

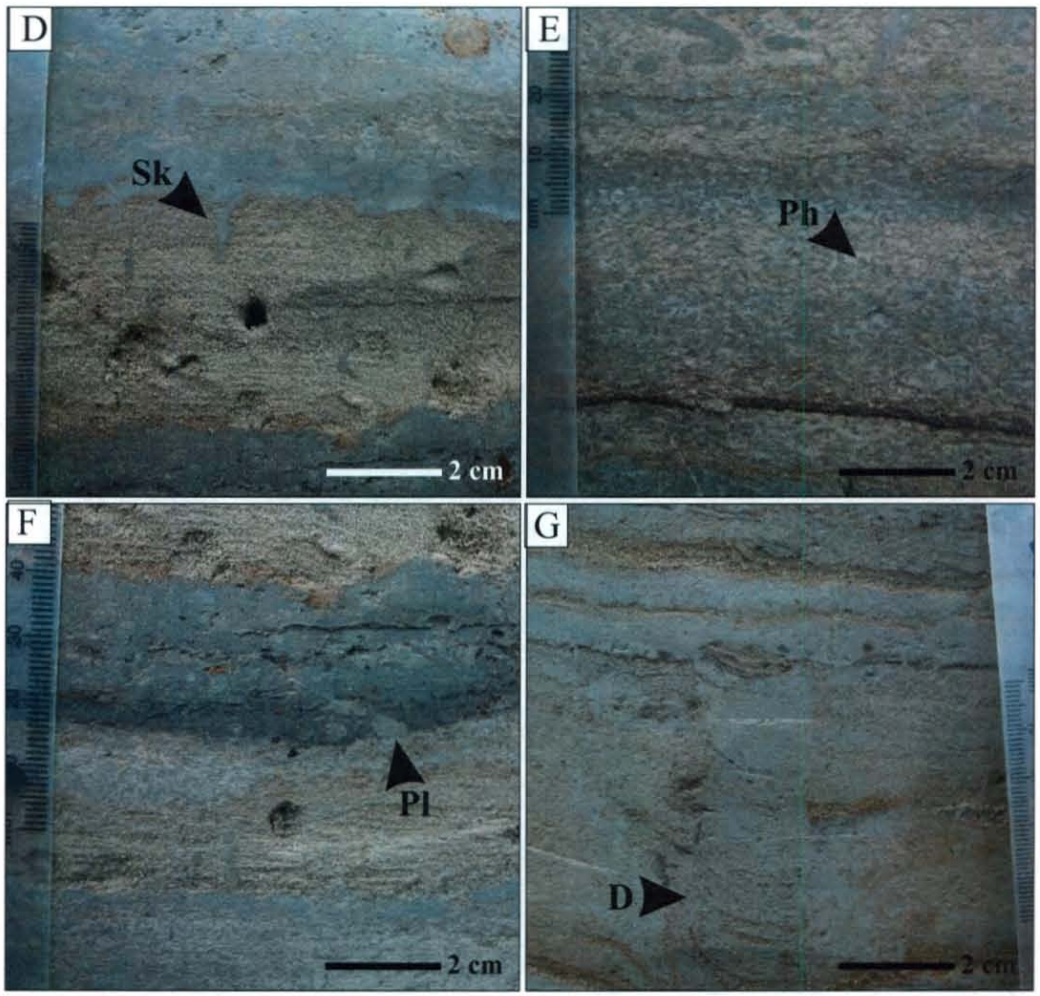


Figure 3.3. Quarternary proximal fan delta plain facies, Conway Flat, New Zealand. **D)** Cross-laminated thin sandstone bed with *Skolithos* (Sk). **E)** *Phycosiphon*-dominated ichnofabric (Ph). **F)** *Planolites* (Pl) in thin carbonaceous mudstone bed. **G)** *Diplocraterion* (D) cross-cutting *Phycosiphon* ichnofabric.

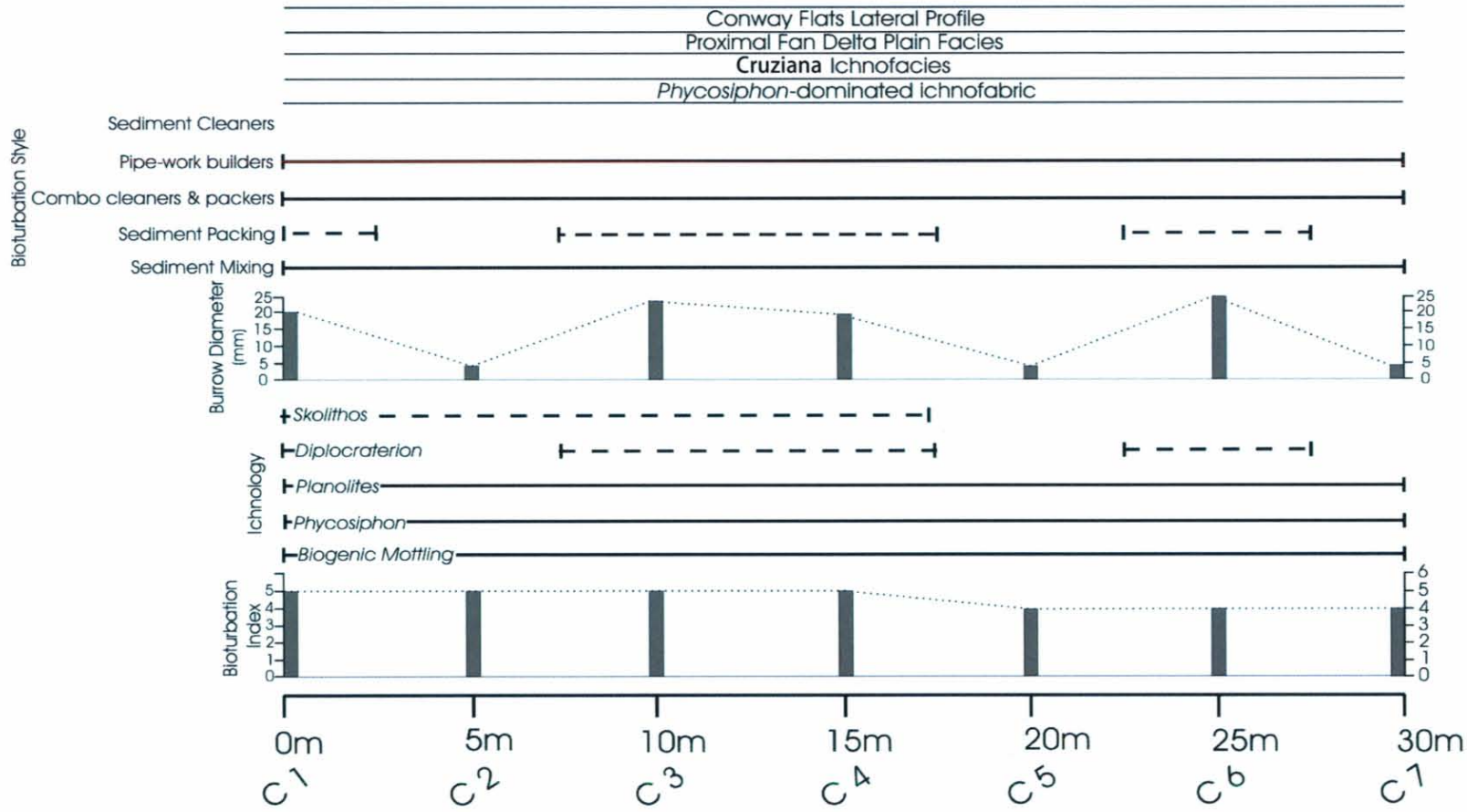


Figure 3.4. Lateral profile of Conway Flats, data summary figure. Bioturbation intensities (BI) range from 4 to 5. Ichnodiversity is moderate, with common *Planolites*, *Phycosiphon*, and biogenic (burrow) mottling (solid black line). Rare *Skolithos* and *Diplocraterion* are also present (dashed black line). Burrow diameters are variable along-strike, and correspond to the presence and absence of the large trace fossil *Diplocraterion*. Sediment mixing, pipe-work building, and combination cleaning-packing styles dominate.

3.3.1. Sedimentological varability

Loess-rich grey bioturbated mud with very thin interbeds of light brown to orange silt to very fine sand, dark grey carbonaceous mud, and grey loessial mud beds are sampled for lateral variability assessment. A dark grey to black carbonaceous mud bed (10-20 mm) with woody fragments, and a laminated to cross-laminated very fine sand bed (10-50 mm) can be traced along strike within the bioturbated mud, forming marker horizons in the 0.4m by 0.4m quadrat (Figure 3.2A). Basal contacts of the carbonaceous and sand beds are typically wavy and erosional into the underlying mud. The thickness of these very thin beds is highly variable, and the beds pinch and swell along strike (Figures 3.2B, and 3.3A-D), with woody particulate and fragments increasing to the north. Laminated to ripple cross-laminated silt to very fine sands also thicken to the north. Small scale syn-sedimentary faults, with offsets of ~50 mm are common in this facies.

The thin section (Figure 3.2C) collected from this mud facies is mainly composed of clay and silt-grade grains (~93%), with lesser amounts of organic material (~5%) and very fine-grained sand (~2%). Very fine-grained sand and coarse silt are moderately sorted, sub-angular to sub-rounded, and spherical to blade-shaped quartz grains. Very fine scale lateral and vertical heterogeneity exists in this facies, within the mud-dominated 0.4 m by 0.4 m areas (Figures 3.2B, and 3.3A-D).

3.3.2 Ichnology

The highest intensities of bioturbation (BI 5) are in the grey mud, and are dominated by pervasive *Phycosiphon* along the horizontal transect. Mud beds contain

common *Planolites,* with rare *Diplocraterion* and *Skolithos*, and abundant burrow-mottled texture. In the carbonaceous mud bed, bioturbation ranges from moderate to high (BI 3 to 5), and is dominated by *Planolites*. The ripple cross-laminated sand beds have low bioturbation intensities (BI 1 to 2), and contain rare *Diplocraterion* and *Skolithos*.

Phycosiphon dominates the loess-rich horizontal transect in this fan delta complex. These mud-filled burrows, <1 mm to 1 mm in diameter with very fine sandy halos, oriented in all directions (Figure 3.3B). This distinctive texture of dark grey curved and hook-shaped burrows is recognized in the mud, silt and very fine-grained sand beds, but is absent in the dark grey carbonaceous mud beds (Goldring *et al.*, 1991; Wetzel and Bromley, 1994; Bednarz and McIlroy, 2009). *Phycosiphon* are cross-cut by large *Diplocraterion* and *Skolithos* (Ekdale and Lewis, 1991) in the loessial mud beds.

Simple horizontal sand- or silt-filled traces of *Planolites* are common in the carbonaceous mud bed, at all intervals along the lateral profile (Figure 3.3C). Burrows are circular to oval in cross-section, and range from 2 mm to 7 mm in diameter. *Planolites* consistently post-date (cross-cut) *Phycosiphon* in loessial grey mud beds, but no other systematic cross-cutting relationships are recognized within the measured vertical surface.

Rare *Diplocraterion* cross-cut multiple beds of grey mud (Figure 3.3D). The spreiten of *Diplocraterion* are alternately composed of mud, and sand, with diameters from 15mm to 26mm, and depths 20 mm to 70 mm (Figure 3.3D). Unlined mud-filled vertical burrows of *Skolithos*, with diameters of 2 mm to 5 mm, and cross-cut *Phycosiphon* and burrow-mottled ichnofabrics (Figure 3.3A).

Observations along a bioturbated horizontal transect reveals a patchy distribution of the four identified ichnotaxa in the Quaternary, Conway Flat section (see summary Figure 3.4). Ichnodiversity is low in the ichnofabric studies, ranging from 2 to 4 ichnotaxon. Maximum burrow diameters range from 5 mm (in *Skolithos*) to 26mm (in *Diplocraterion*) along strike. Ichnofabrics can be categorized as *Phycosiphon*-dominated or *Phycosiphon-Diplocraterion,* and *Planolites*-dominated. Alternatively, using the ichnofacies approach, the lateral profile bed is assigned the *Cruziana* ichnofacies.

Bioturbation styles across the profile are dominated by burrows of combination cleaner-packing (e.g. *Phycosiphon*), sediment mixing (e.g. burrow-mottling texture), and pipe-work building strategies of *Planolites* and *Skolithos*. Rare examples of sediment packing bioturbation style (*Diplocraterion*) are associated with the thin carbonaceous mud, and ripple cross-laminated sand beds.

3.3.3 Discussion

The loess-rich mud is intensely bioturbated (BI 5), and in some cases homogenized, these characteristics reflect low sedimentation rates relative to the rate of bioturbation. The lower delta plain facies is inferred to have been well-oxygenated with abundant food supply in the form of detrital organic matter. Bioturbation intensity in the storm-induced sand beds is generally low (BI 1 to 3), as these event beds are related to rapid deposition of storm washover sheets. Rare root traces are not related to the studied beds, but have penetrated from the stratigraphically higher rhizolith facies in the section.

The heterolithic facies form the marginal marine component of a fan delta complex (Ekdale and Lewis, 1991; Figures 3.2, 3.3 and 3.4). This ichnological

investigation focused on a back barrier, lagoonal facies, with inter-bedded terrigenous matter and ripple cross-laminated sand bed. These thin event beds erode into underlying mud, suggesting fluctuating hydrodynamic energy and rapid deposition during episodic flooding, and storm washover events. The highly variable bioturbation intensity (BI 1 to 5) of the beds is a direct result of the episodic high fluvial discharge (allowing time for organisms to colonize substrate between depositional events), and associated high sedimentation rates (impeding rate of bioturbation) on the flood-prone lower delta plain.

The lateral profile at Conway Flat is dominated by fair-weather *Phycosiphon*-dominated ichnofabrics, with event bed *Planolites* ichnofabrics (Figure 3.4). Sedimentation rates are variable, and consist of episodic, storm (sand) and flood-related (carbonaceous mud) deposition. The bioturbation style is dominated by sediment mixing and combination cleaning-packing with, similar ichnofabrics along the short lateral distance of 30 m.

3.4. Shoreface succession (Neslen Formation, Book Cliffs, Utah, USA)

In the late Cretaceous, continental collision of the Pacific Plate and the North American Plate produced high mountains in western Utah, while eastern Utah was drowned by seas from the east (Kauffman, 1984). This tectonically induced transgression of eastern Utah formed an inland sea, and a coastal plain developed between the east and west coal swamps (Franczyk *et al.*, 1992). Foreland basin deposition took place during the Sevier Orogeny (Cross, 1986), and is characterized by a range of siliciclastic shallow marine facies. A variety of depositional environments have been interpreted in the upper

Cretaceous strata of eastern Book Cliffs including coastal plain, estuarine, shoreface, delta front and offshore marine (e.g. Sego Sandstone, Neslen Formation and Castlegate Sandstone of the Mesaverde Group; Swift *et al.*, 1987; Van Wagoner, 1995; Willis, 2000; Kirschbaum and Hettinger, 2004; Pattison *et al.*, 2007). *Ophiomorpha*-dominated ichnofabrics of the Sego Sandstone (stratigraphically below the Neslen Formation) reveal variations in burrow architecture of *Ophiomorpha* that are controlled by hydrodynamic energy, grain size and sedimentation rate (Anderson and Droser, 1998). The present study has focused on a single upward coarsening succession (parasequence) of well-cemented heterolithic mudstones, and siltstones inter-bedded with muddy very fine grained hummocky cross stratified (HCS) sandstones of the Neslen Formation (Figure 3.5). The HCS sandstone beds become amalgamated at the top of the succession indicating deposition in the middle shoreface. Cliff-line exposures of the Neslen Formation at Sagers Canyon, Book Cliffs, Eastern Utah were sampled along at 10 m intervals along a laterally continuous exposure (Figures 3.5 and 3.6A).

3.4.1 Sedimentological variability

The studied horizon is very fine grained, well-cemented, sandstone from within a thick 12 m heterolithic succession of hummocky cross-stratified laminated mudstones and bioturbated siltstones. The thickness of the sandstone bed was found to vary laterally from 0.13 to 0.22 m. The basal contact with the underlying heterolithic facies is wavy and erosive. Parallel laminae (<1 mm to 1 mm spacing) are present in the basal portion of the bed in all samples, with the exception of SC11. The upper portion of the sandstone is apparently massive with no grading apparent in hand specimen. When studied in large

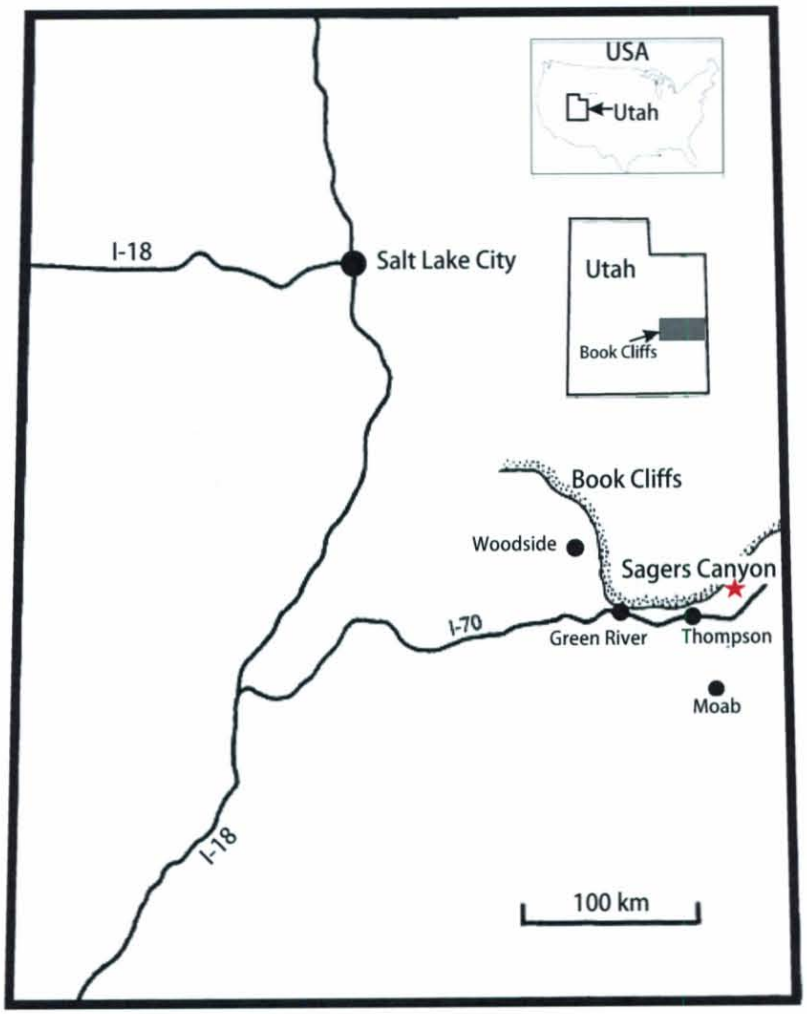


Figure 3.5. Locality map of Sagers Canyon, Book Cliffs, Utah, USA. (taken from Anderson and Droser, 1998). The 50 m lateral profile was sampled from a cliff-line section.

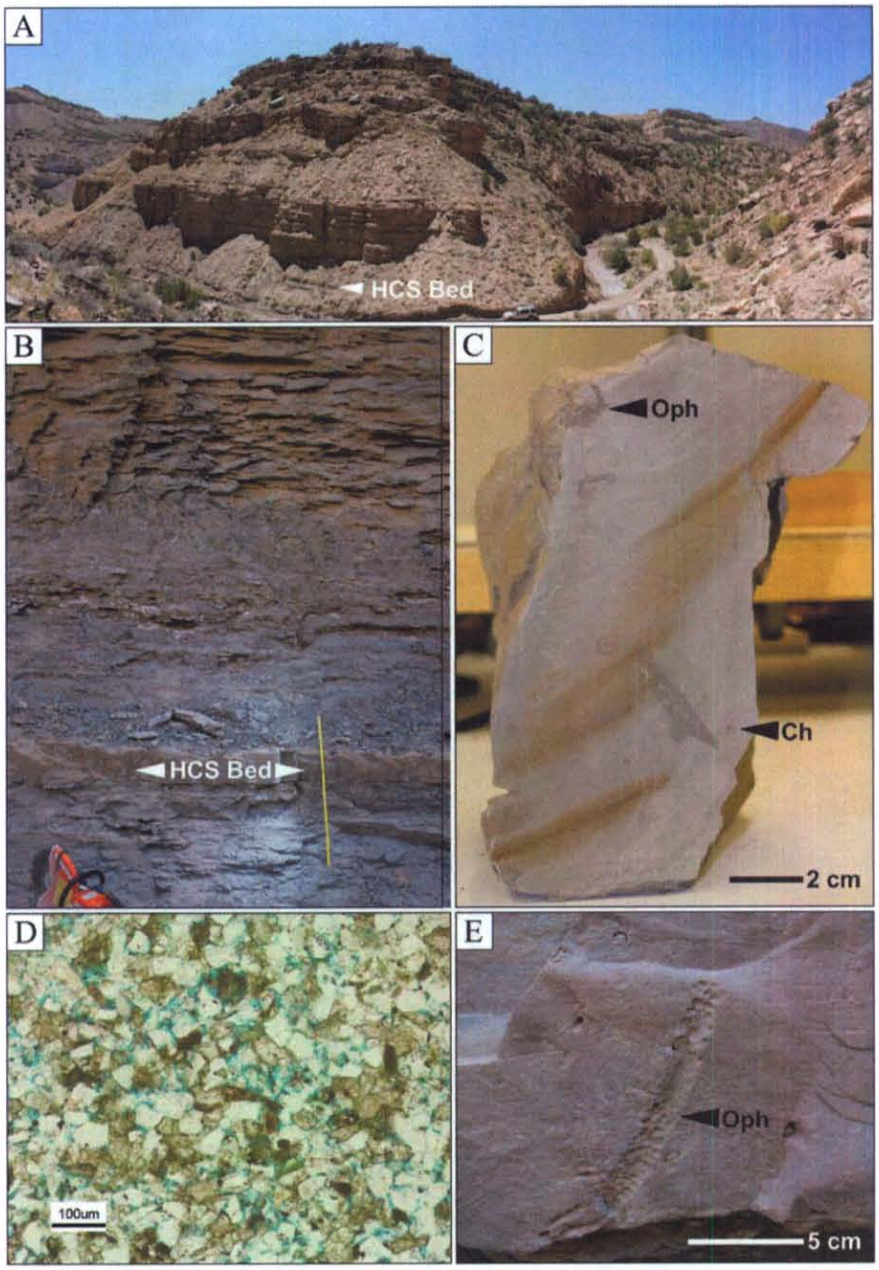


Figure 3.6. Shoreface succession, Late Cretaceous Neslen Formation, Book Cliffs, Utah. **A)** View of offshore to shoreface succession in Sagers Canyon, Book Cliffs, Utah. **B)** Hummocky cross- stratified (HCS) bed interbedded within heterolithic lower shoreface facies. **C)** *Ophiomorpha* (Oph) and *Chondrites* (Ch) in cut slab sample of SC11 from HCS lateral profile bed. **D)** Photomicrograph of HCS lateral profile bed. Thin section is impregnated with blue epoxy, blue color shows pore space. **E**) Vertical shaft of *Ophiomorpha* (Oph) burrow in hummocky cross-stratified (HCS) bed.

thin slice, the massive fabric is resolved as very low angle, fuzzy lamination (Figures 3.7A-3.7E).

The samples are from the same muddy very fine-grained sandstone bed, which calcareously cemented. Petrographic characteristics are similar along-strike, all samples are composed of clay, silt, and very fine sand fractions, and are moderately sorted, with a calcitic or clay-mineral cements (Figure 3.6D). In sample SC3, the proportions of lowered calcite (25%), and proportionally higher clay content (40%) coincide with the presence of an *Ophiomorpha* burrow. Sedimentological characteristics are homogenous along strike in this hummocky cross-stratified bed (HCS).

3.4.2 Ichnology

Bioturbation intensity is consistently 10-20% across the length of the studied bed (BI2 of Taylor and Goldring, 1993). Discrete trace fossils of *Phycosiphon*,*Cylindr ichnus* and *Ophiomorpha* overprint the prevalent fuzzy lamination which is interpreted as cryptobioturbation (Figures 3.7A-3.7E).

Mudstone-filled *Phycosiphon* (<1mm diameter) are common within the HCS bed as moderate intensity clusters of "frogspawn texture" (cf. Bednarz and McIlroy, 2010; Figures 3.7A-3.7E). *Phycosiphon* is only visible in large thin slices, as weathering and cement obscure these tiny burrow structures under normal light in hand sample (Figures 3.7B and 3.7C).

Ophiomorpha irregulaire (18 mm diameter) are recorded in cut slab sample SC7 only despite being the most abundant and conspicuous trace fossil in outcrop, and uncut sample faces (SC3, SC5, and SC9, 9-20 mm diameter). *Ophiomorpha irregulaire*

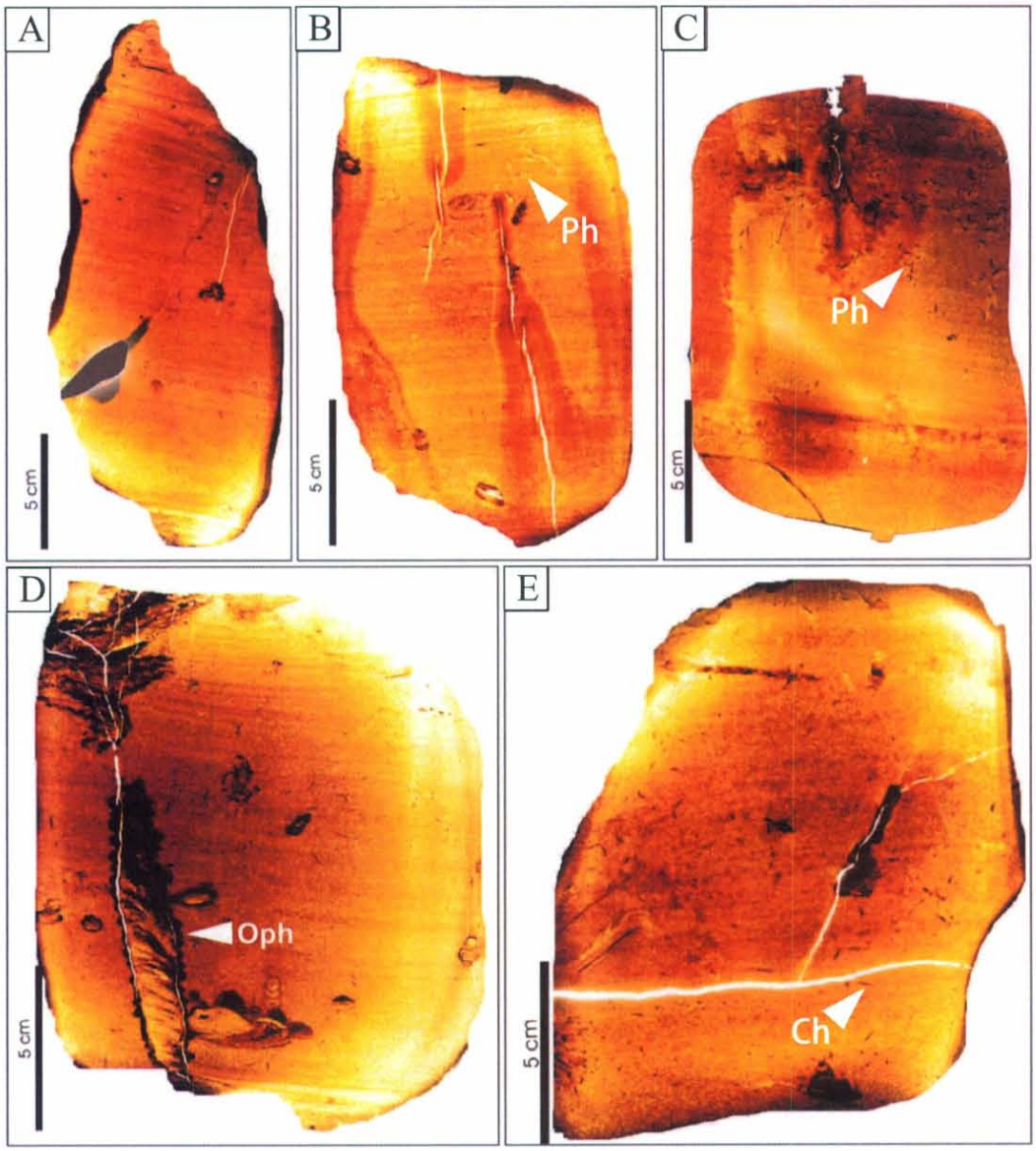


Figure 3.7. Shoreface succession, Late Cretaceous Neslen Formation, Book Cliffs, Utah. **A)** Low-angle "fuzzy" (=cryptobioturbation) lamination in large thin slice image of sample SC3 at 10m. **B)** Sparse patches of *Phycosiphon* (Ph), and cryptobioturbation in large thin slice image of sample SC5 at 20m. **C)** Dense patches of *Phycosiphon* (Ph), and cryptobioturbation in large thin slice image of sample SC7 at 30m. **D)** Vertical shaft of *Ophiomorpha* (Oph) in large thin slice image of sample SC9 at 40m. **E)** *Chondrites* (Ch) and cryptobioturbation in large thin slice image of sample SC11 at 50m.

burrows are lined with circular to oval mudstone-rich pellets (1-3 mm pellet diameter) and its recognition in outcrop and core has been the subject of some debate (Bromley and Petersen, 2008; McIlroy *et al.*, 2009). Some *Ophiomorpha* are passively infilled with alternating sandstone and mudstone laminae (Figure 3.7D). *Ophiomorpha* have vertical to inclined shafts and bedding parallel galleries and are cross-cut by *Phycosiphon.*

Cylindrichnus (8-16 mm diameter) is circular to ovoid in cross-section, with concentric mudstone-rich fill, vertical to inclined to bedding, and often tapers into a cone shape (Howard and Frey, 1984). This trace is not visible in any of the cut slab faces along the lateral profile, but was common in the field and present in uncut sample faces of SC3, SC5, SC7 and SC11.

Analysis of the cut slab samples along a bioturbated horizontal transect reveals distribution of *Phycosiphon* and *Ophiomorpha* in the Neslen Formation, Book Cliffs, Utah (see summary Figure 3.8). *Cylindrichnus* is omitted from the quantitative dataset, as it is not present in the cross-section of any of the random samples. In the cut slab sample data set, cryptobioturbation and *Phycosiphon* traces are common. Ichnofabrics are variable are comprised of *Phycosiphon* (SC1, SC5, SC9 and SC11), cryptobioturbation (SC3), and *Ophiomorpha* (SC7). Using the ichnofacies approach, most samples would fall within either the archetypal *Cruziana* ichnofacies (SC1, SC3, SC5, SC9 and SC11) or stressed proximal *Cruziana* ichnofacies, and the archetypal *Cruziana* ichnofacies for sample SC7 (cf. MacEachern *et al.*, 2010). Ichnodiversity is low and ranges from 1 to 2 identified ichnotaxa. The maximum burrow diameter of trace fossils at each sample point ranges from >1mm *Phycosiphon* to 18 mm in the single *Ophiomorpha*. Bioturbation styles (Chapter 2, Tonkin *et al.*, 2010) across the profile are

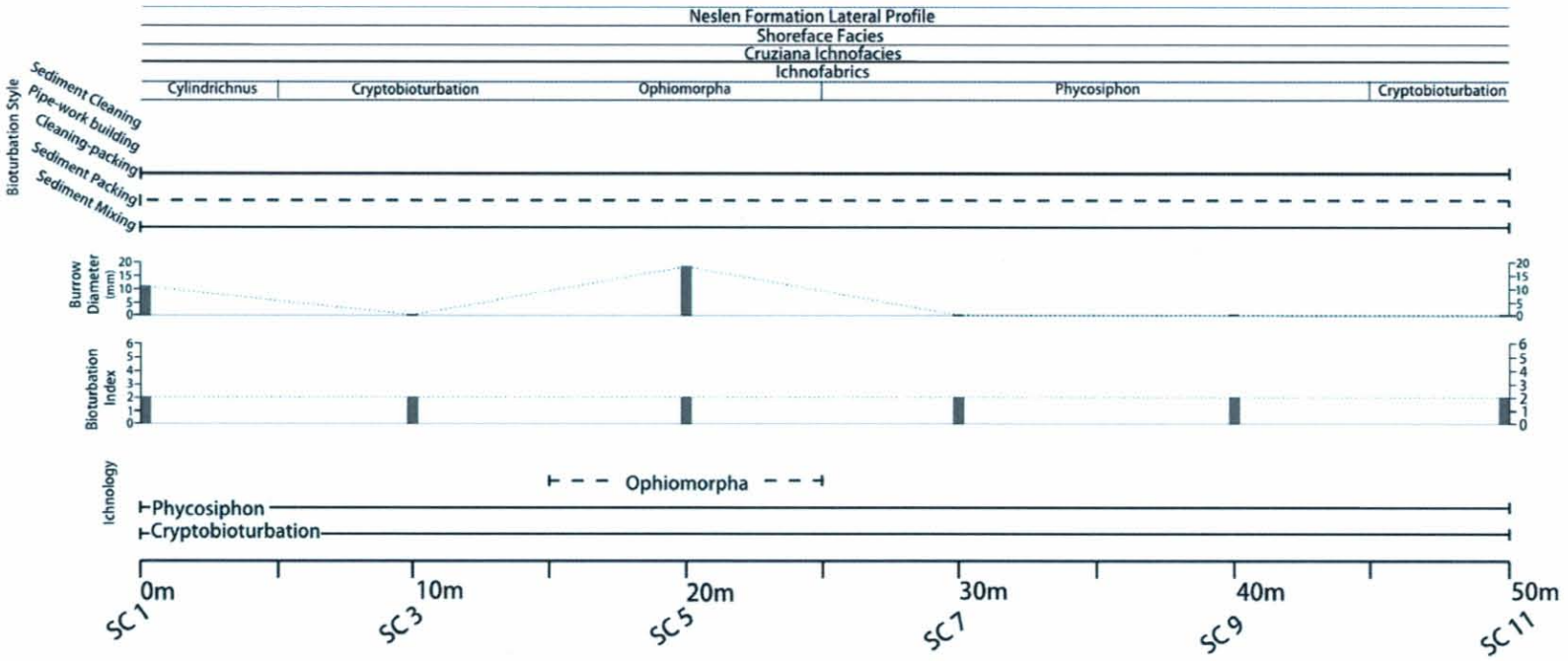


Figure 3.8. Lateral profile of Neslen Formation, data summary figure. Ichnodiversity is low, with common *Phycosiphon*, and cryptobioturbation (solid black line). Rare *Ophiomorpha* are also present (dashed black line). Bioturbation intensity (BI) is low at 2, with preserved laminae in this HCS bed. Burrow diameters are variable along-strike, and correspond to the presence or absence of the large trace fossil *Ophiomorpha*. Sediment mixing, and combination cleaning-packing styles dominate.

dominated by sediment mixing (e.g. cryptobioturbation), with the combined cleaning-packing behaviours (e.g. *Phycosiphon*) being common, and more rarely sediment packing (*Ophiomorpha*).

3.4.3 Discussion

The calcareous sandy siltstone bed sampled for the lateral profile study is consistent with deposition shoreface setting, and interpreted to be a storm-induced HCS bed (Figures 3.6, 3.7 and 3.8). Deposition is inferred to have been above storm wave base, but below fair weather wave base. The source of sand is interpreted to be from beaches and mouthbars, eroded during storm conditions, and re-deposited in the lower shoreface and offshore transition zone to create sheet-like sandstone geometries (Dumas and Arnott, 2006).

The HCS bed studied herein has an undulating erosive basal contact with the underlying background heterolithic package. The bulk of the HCS bed consists of cross laminae with a fuzzy appearance, this post-depositional modification may have formed biogenically by meiofaunal cryptobioturbation (Howard and Frey, 1975) or by small-scale physically-induced dewatering or liquefaction (Owen, 1996; Hildebrandt and Egenhoff, 2007). It is considered difficult to distinguish between these possibilities for lack of objective recognition criteria. In this thesis the fuzzy laminated texture is termed cryptobioturbation.

Ichnodiversity of the HCS storm-induced event is impoverished relative to the enclosing highly bioturbated heterolithic interbeds. Bioturbation styles are relatively similar in all samples, with sediment mixing and combined sediment cleaning-mixing

strategies volumetrically dominant in the bed. In outcrop exposure *Ophiomorpha* and *Cylindrichnus* are conspicuous components of the ichnofabric (Figures 3.6C and 3.6E), but the field observations are not reflected in sample dataset. In addition, while *Phycosiphon* were not noted in outcrop or uncut sample surfaces, they are common in large thin slices, and demonstrate observational biases from field to slab samples.

Bioturbation intensity and ichnodiversity of trace fossils are low in all samples and are laterally unvarying in the sample dataset. *Ophiomorpha* and *Phycosiphon* consistently overprint the prevalent fuzzy laminated texture (crytobioturbation or dewatering), this relationship suggests either that the original sediment mixing community predates the subsequent larger traces or that there is mutual avoidance. Post-event colonization of the HCS sandstone by *Ophiomorpha*, *Phycosiphon* and *Cylindrichnus* is considered to have been short-lived since bioturbation intensity is low (BI 2) relative to the intense bioturbation characteristic of the enclosing fair-weather facies.

In summary, physical and biogenic sedimentary structures, and petrography do not vary significantly in the present study (Figure 3.8). This homogeneity is taken to imply little discernable patchiness and a lack of significant biological stress in the post-event ecosystem. Observation of any slab (in retrospect) would have been acceptable for facies characterization of the bed throughout the lateral profile.

3.5 Offshore shelf (Pohutu Formation, Raukumara Basin, New Zealand)

The late Miocene to early Pliocene age strata of East Cape, Raukumara Peninsula, New Zealand were deposited in a forearc basin located along the Hikurangi convergent plate boundary. This open coast marine succession of siliciclastic rocks has high volcaniclastic input because of its proximity to the active Coromandel Volcanic Arc during the Neogene (Adams *et al.*, 1994). Tuff beds are re-deposited as volcaniclastic sediment gravity flows, from influx of material into the basin via fluvial transport (Ballance *et al.*, 1991; Shane *et al.*, 1998). These strata comprise the Paeoneone and Pohutu Formations of the Mangaheia Group (Mazengarb *et al.*, 1991), and are now recognized as potential analogous reservoir facies to those offshore in the Raukumara Basin (Stagpoole *et al.*, 2008). The petroleum potential of the Raukumara Basin has been identified from 2D seismic data (RAU07), direct hydrocarbon indicators, and seismic facies of shelf and turbidite sandstones are interpreted as potential reservoirs (Uruski *et al.*, 2008).

The background mudstones, siltstones and very fine sandstones of the Pohutu and Paeoneone Formations are interbedded with sediment gravity flows (slumps, turbidites, debris and grain flows) and tuff horizons (Ballance *et al.*, 1991). The majority of these sediment gravity flows are bioturbated, have erosional bases and are of rhyolitic volcanic origin. The upper-slope to outer-shelf marine succession of the Pohutu Formation coarsens upwards, and is in gradational contact with the sandier Paeoneone Formation. Bioturbation is intense in most beds, and trace fossils are well-preserved, owing to the strong lithological contrasting between the dark grey lithic mudstones and sandstones, and light-colored volcaniclastic burrow fill.

Samples were taken from a bedset exposed in a wave cut platform, close to the gradational boundary between the Pohutu and Paeoneone formations, at Whararíki Point, along 60 m of outcrop at 5 m intervals (Figure 3.9). Siliciclastic mudstones, siltstones and sandstones are inter-bedded with volcaniclastic rocks of Neogene age in Pohutu Formation upper slope to outer shelf depositional settings (Ballance *et al.*, 1991). The shallowing upward succession of grey sandy mudstone facies are interbedded with reworked rhyolitic tuff beds. The studied bed runs parallel to the present day coastline in a NW/SE strike direction. The length of the lateral profile was limited due to erosion and small scale faulting in the section, but represents the longest continuous exposure available for study.

3.5.1 Sedimentological variability

Sandy mudstone is interbedded with two thin tuff beds, and are sampled to assess the lateral ichnological and sedimentological variability. The lower pale-grey to white fine-grained tuff ranges from 20-50 mm thickness along strike in the 60 m profile (Figure 3.10A). The basal contact with the underlying mudstone is highly variable, being irregular, and either sharp or diffusely bioturbated. The upper cream to orange colored, pumice-rich coarse-grained volcanic tuff bed is between 60 and 120 mm thick, and lies directly above the lower fine tuff or above a thin bed of sandy mudstone between the two tuff beds. The enclosing sandy mudstone is absent of sedimentary structures due to intense bioturbation (BI5). Sedimentary structures in the pyroclastic tuff beds are rare, but include wavy, irregular thin (1-3 mm) laminae are recognized in the basal 0-30 mm of the coarse tuff bed of sample EC12 (Figure 3.10B). Bivalve shell fragments (<5 mm) are

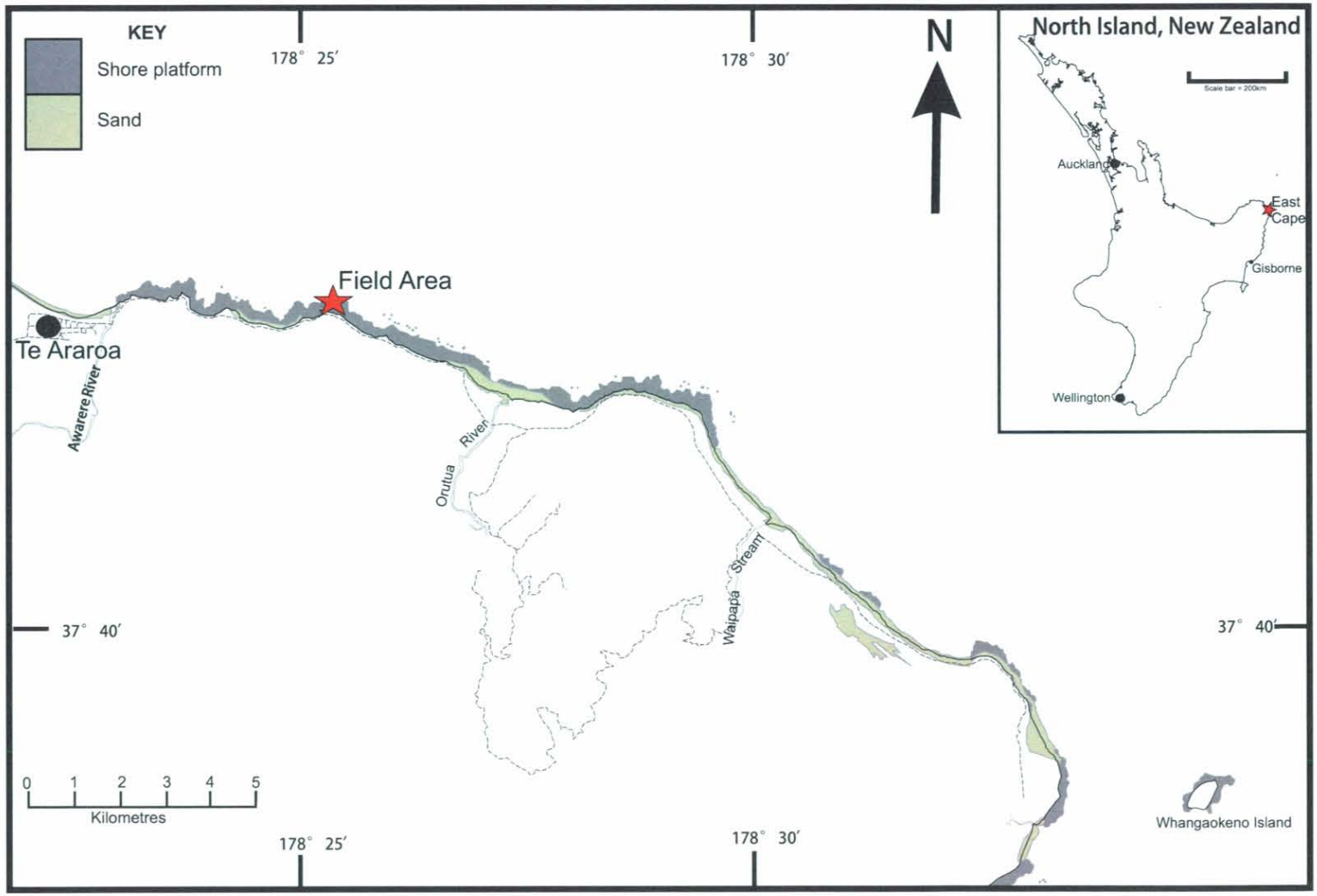


Figure 3.9. Locality map of Pohutu Formation, East Cape, North Island, New Zealand. Lateral profile was sampled along a 60 m length shore platform exposure.

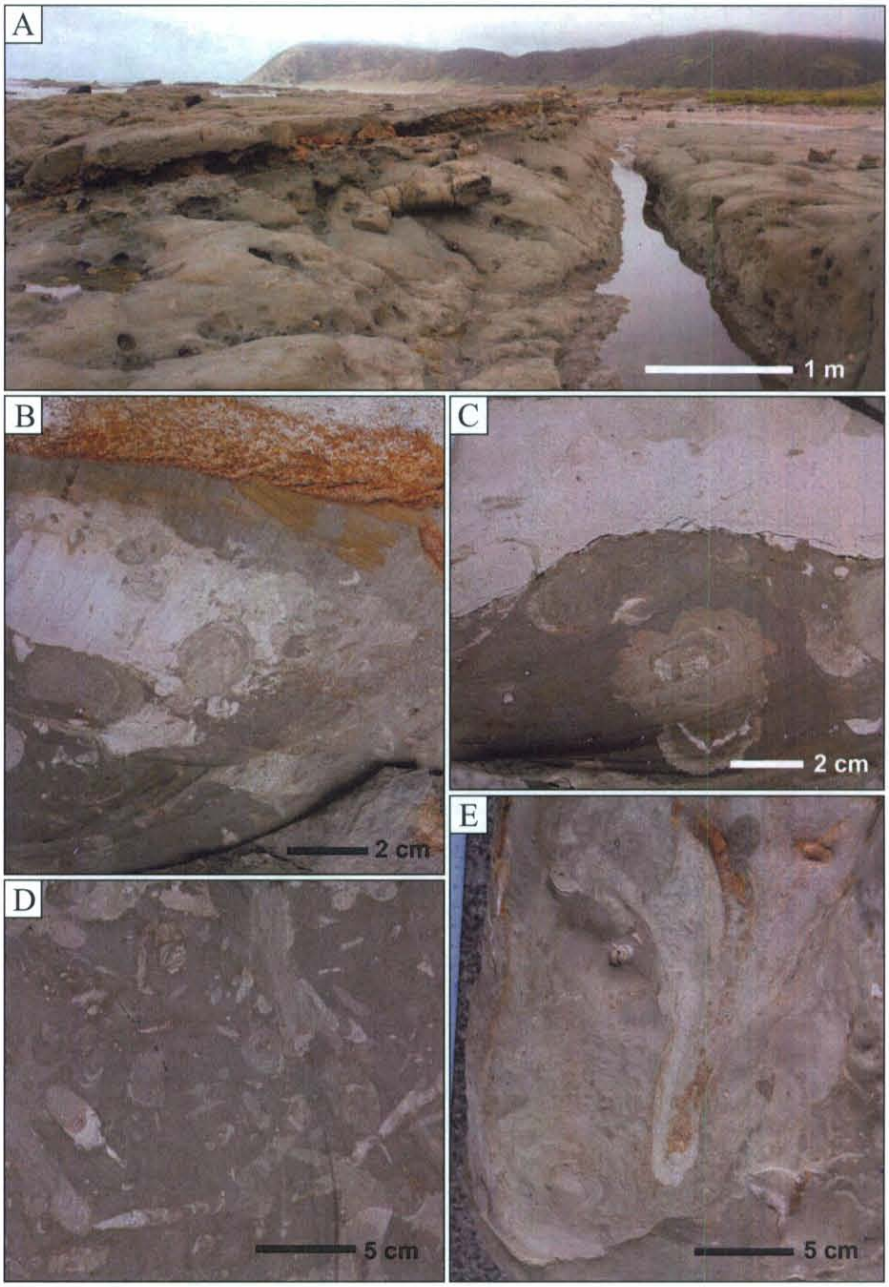


Figure 3.10. Shelfal succession, Pohutu Formation, East Cape, Raukumara Peninsula, New Zealand. **A)** Along-strike view of lateral profile bed west of Whararíki Point, East Cape. **B)** Fine- and coarse-grained tuff interbedded within sandy mudstone. Rare preservation of lamination in base of coarse tuff bed (slab sample EC5 at 20m). **C)** Erosive contact between fine-grained tuff and background sandy mudstone with *Asterosoma* burrow (slab sample EC3 at 10m). **D)** *Teichnichnus*-dominated bedding plane surface (slab sample EC7 at 30m). **E)** Cross-section through vertical shaft of *Asterosoma* (uncut slab sample EC10 at 45m).

dispersed throughout the mudstone, but are absent in the tuff beds. Most samples contained both a bioturbated fine-grained tuff and a coarse tuff bed. The discontinuous lateral distribution of the tuff beds in the sample is a product of the erosive, undulating contact both volcaniclastic beds with the underlying sandy mudstone (EC5, EC6, Figures 3.107B, 3.10C, and 3.11A). In localities with deeper erosion (e.g. below the upper tuff) the thin tuff beds are stacked, and the intercalated mudstone bed is not preserved.

Color and lithological contrast are commonly the only evidence of bedding in this study. As a consequence of the lack of physical sedimentary structures in the Pohutu Formation, ichnological and other paleontological analyses are the basis of the paleoenvironmental interpretation.

3.5.2 Ichnology

Bioturbation intensity ranges from BI 4 to 5 (61-99%) along strike in the lateral profile. The sandy mudstone consistently has intense bioturbation (BI 5), dominated by *Asterosoma*. In both the fine- and coarse-grained tuff beds, bioturbation is intense (BI 4 to 5), with laminae only rarely preserved (EC12). *Phycosiphon*, *Teichichnus*, *Scolicia*, *Chondrites*, *Planolites*, *Thalassinoides*, and ambient burrow-mottled textures are recorded from cut slab faces. Along-strike ichnodiversity is variable (1 to 4 discrete ichnotaxa, Figures 3.10B-3.10E, and 3.11C).

Burrow diameters of *Asterosoma* range from 15 to 90 mm, with concentrically laminated sandstone or alternating tuff-mudstone burrow fill in most of the samples (cross sections of shafts and arms, Figures 3.10C and 3.10E). At, or near bedding contacts with tuff, all burrows are readily seen, and both the vertical shafts and

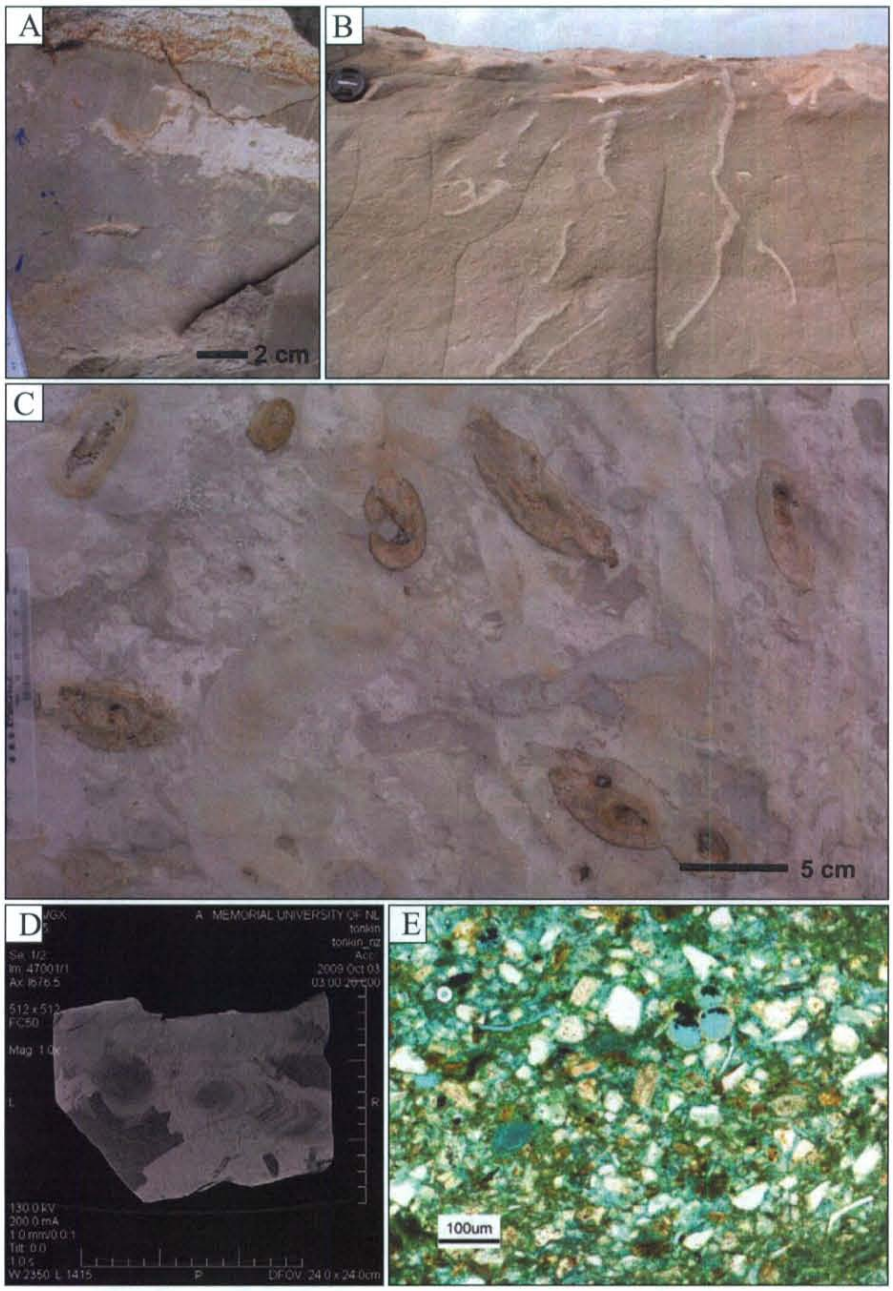


Figure 3.11. Shelfal succession, Pohutu Formation, East Cape, Raukumara Peninsula, New Zealand. **A)** Burrow mottled ichnofabric, with *Phycosiphon*. Note discontinuous tuff bed (slab sample EC13 at 60m). **B)** Vertical section adjacent to EC10 sample, with fine ash-filled *Teichichnus* below. **C)** Bedding plane view of *Scolicia* adjacent to sample EC9. **D)** CT scan image of EC3, *Scolicia* and biogenic (burrow) mottling. Image highlights the mineralogical contrasts between the tuff and mudstone. **E)** Photomicrograph of sandy mudstone (sample EC1). Thin section is impregnated with blue epoxy, blue color shows pore space.

longitudinal/transverse sections through the radial arms of *Asterosoma* are determined. A complete burrow system with both central shaft and radiating arms is visible sample EC10, and in outcrop (Figure 3.10E). *Asterosoma* burrows in sample EC9 and EC10 have a central core of coarse-grained tuffaceous fill, linking them to an overlying sediment water interface at a depth of tiering of 0.15m (Figure 3.10E).

Phycosiphon are common in small patches in the sandy mudstone facies. The dark mudstone-filled burrow cores are up to 1mm in diameter with slightly lighter silt-grade haloes. *Phycosiphon* cross-cuts *Asterosoma* in samples EC7 and EC8. This small trace is difficult to distinguish from background burrow-mottled texture in the field, having little lithological contrast, and therefore may be more prevalent than recorded herein.

Chondrites are rare and variably distributed in the sandy mudstone. The burrows are generally filled with fine-grained tuff. The branches of *Chondrites* are 1 to 3mm in diameter, and are orientated subparallel to bedding (Figure 3.11A). No systematic cross-cutting relationships are recognized in relation to other ichnotaxa and the vertical shaft is not documented herein.

Horizontal, circular to ovoid cross sections of *Planolites* are present in samples EC1 and EC6 only. The burrows are fine tuff or sandstone-filled in contrast to enclosing rock, and range from 3 mm to 12 mm in diameter. *Planolites* have wavy margins, and no systematic cross-cutting relationships are observed. *Thalassinoides* is present in samples EC1, and EC3 to EC5, and is found to be filled with fine-grained tuff or mudstone, in lithological contrast to enclosing lithology. Horizontal burrows of *Thalssinoides* range

from 7 mm to 27 mm in diameter and cross-cutting relationships with other ichnotaxa are not observed.

Scolicia is rarely observed in vertical sections of samples (EC3), but are commonly seen in outcrop at the interface between mudstone and tuff beds (Figure 3.11C). Burrow is 25mm diameter and visible an X-ray image of sample EC3 (Figure 3.11D). Alternating mudstone and tuff meniscate backfill makes this horizontal *Scolica* burrow conspicuous in the EC3 sample. Tuff is likely a constituent of all samples across the profile, as in bedding planes in outcrop.

Teichichnus zig-zag (Frey and Bromley, 1985; Martin and Pollard, 1996) is rare in the stratigraphic interval sampled except in sample. The inclined burrows have diameters of between 5 mm and 10 mm. Burrow fill is either fine-grained tuff, or alternating tuff and sandstone within mudstone host sediment. Burrows of *Teichichnus* mutually cross-cut one another and have wavy margins. *Teichichnus* is common in outcrop, below and adjacent to sample points along the lateral profile (Figures 3.10D and 3.11B). The case for potential over-representation of *Teichichnus* in sample EC7 is interesting. The importance of this ichnotaxon could easily have been over-interpreted had that point been intersected in a core-based study in the subsurface.

Circular to ovoid coarse tuff-filled burrows are present in the mudstone facies. Burrow margins are sharp with diameters ranging from 7 to 12 mm, in horizontal and vertical orientations in samples EC1, EC4, EC11 and EC13. In samples where discrete trace fossils are not discernible, or where discrete traces overprint intensely bioturbated ichnofabrics, this biogenic texture is named burrow-mottling and occurs where

lithological contrast is low or the sample is intensely bioturbated (Figures 3.10B-3.10E, and 3.11A-3.11E).

Sampling along the lateral transect reveals patchy distribution of the seven identified ichnotaxa in the upper Pohutu Formation, Raukumara Basin, New Zealand (see summary Figure 3.12). *Asterosoma* and *Phycosiphon* dominate the ichnofabrics, with accessory ichnotaxa being *Chondrites*, *Scolicia*, *Thalassinoides*, *Planolites* and *Teichichnus*. The ichnofabrics seen are subdivided conservatively into: *Asterosoma*-dominated ichnofabrics (EC2-6; EC8-12), burrow-mottled ichnofabric (EC1), and a *Teichichnus-Phycosiphon* (EC7) ichnofabric. Alternatively, using the ichnofacies approach, all sample point along beds would be grouped into the *Cruziana* ichnofacies, with the exception of EC1. Ichnodiversity is low to moderate in all ichnofabrics, and ranges from 2 to 4 identified ichnotaxa. The total ichnodiversity of the lateral profile is 7 ichnotaxa. Maximum burrow diameters range from 12mm to 90mm along strike and are usually attributable to *Asterosoma*, or *Planolites*.

Bioturbation styles across the profile are dominated by sediment mixing (e.g. mottling texture), with common sediment packing (*Asterosoma* and *Scolicia*), and combination cleaner-packers (e.g. *Phycosiphon*; Tonkin *et al.*, 2010). Minor pipe-work building *Thalassinoides* and *Planolites* are also present in low abundance in EC1, EC3 to EC9 samples (Figure 3.12).

3.5.3 Discussion

The intensely bioturbated sandy mudstones of the Pohutu Formation are inferred to have been deposited on a wave/storm-dominated shelf paleoenvironment.

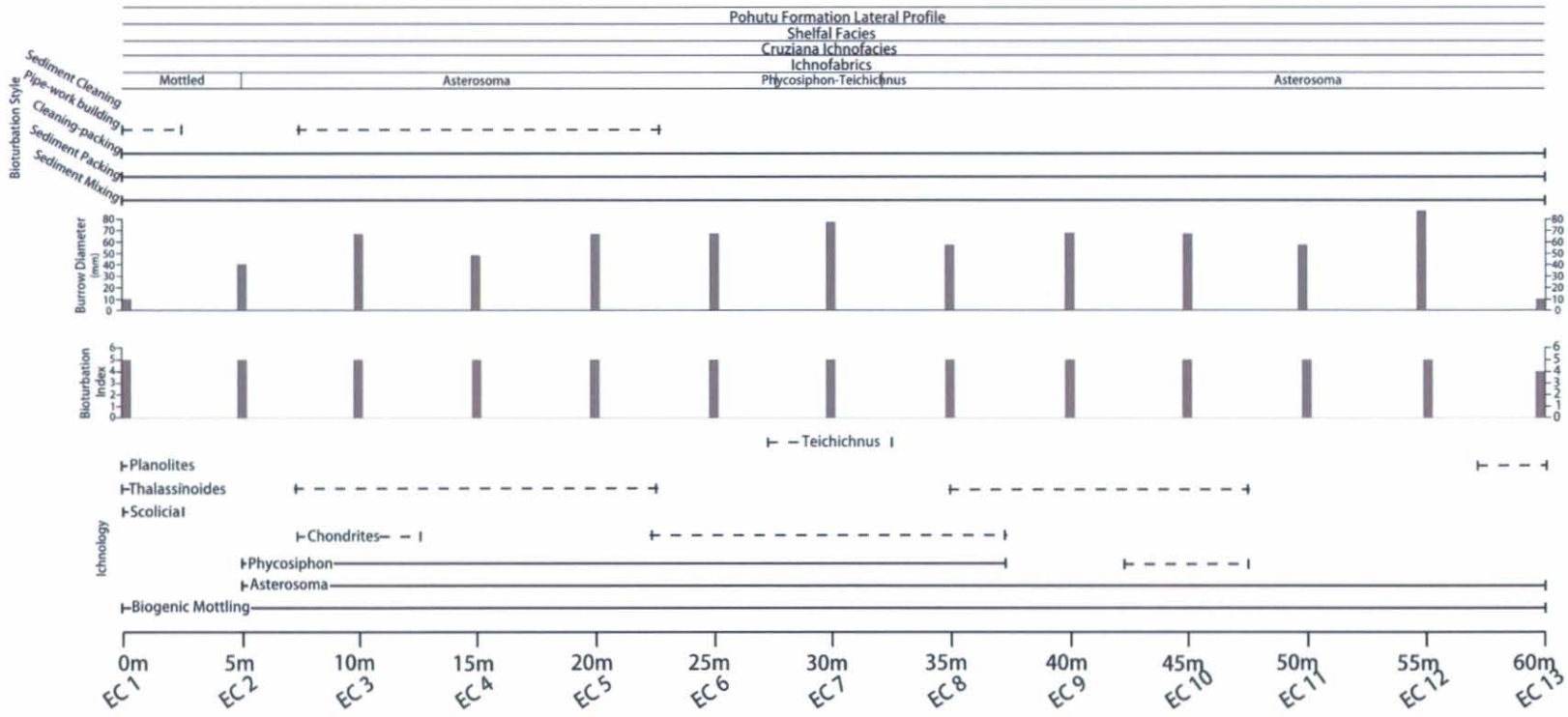


Figure 3.12. Lateral profile of Pohutu Fomration, data summary figure. Ichnodiversity is moderate, with common *Asterosoma*, *Phycosiphon*, and burrow-mottling (solid black line). Rare *Chondrites*, *Planolites*, *Scolicia*, and *Thalassinoides* are also present (dashed black line). Bioturbation intensitiy (BI) is high at 5. Burrow diameters are variable along-strike, and correspond to the presence or absence of the large trace fossil of *Asterosoma*. Sediment mixing, packing, and combination cleaning-packing

Sedimentation rate on the outer shelf is inferred to have been low based on the high bioturbation intensity, but is punctuated by episodic rapid deposition of reworked pyroclastic tephra. Tuff has also been biogenically mixed into the intensely bioturbated sandy mudstone, and sourced from air-fall tephra, and subsequent suspension settling (Figures 3.10B-3.10E). This mudstone is considered to be the background fair-weather facies on the outer shelf. The reworked subaqueous tuffs are likely to be deposited by sediment gravity flows generated by rapid deposition of fluvial-derived pyroclastic material onto the inner shelf (Fisher, 1984). The type of sediment gravity flow is difficult to define, as only rare sedimentary structures are preserved in tuff beds. The presence of complete Bouma sequences in the upper-slope facies elsewhere in the lower Pohutu Formation (Einsele *et al.*, 1991) suggests that they were deposited by either debris flows or turbidity currents. The mudstone/siltstone-rich outer shelf facies are inferred to have been sourced from a fluvio-deltaic system which supplied a mix of siliciclastic and volcaniclastic sediments to the Raukumara Basin.

Softground substrates are recognized over the short vertical section (1.0-1.5 m) as defined by wavy burrow margins of trace fossils (Figures 3.10B, 3.10C and 3.10D). Periods of non-deposition allowed for development of firmground conditions (reflected in the ichnological assemblage). An alternative hypothesis is exhumation of a firmground by erosive sediment gravity flows. Previous authors have discussed winnowing out of clay-size fraction of sediments by bottom water currents produced by geostrophic flow (Swift and Thorne, 1991; Ballance *et al.*, 1991). The low mud content in the wave/storm-dominated shelfal facies suggests clay-grade sediment was being transported offshore to deeper slope facies (Ballance *et al.*, 1991, MacQuaker and Gawthorpe, 1993). This

interpretation is confirmed by abundance of silt-size grains in thin section, and the locality of the beds on the shelf are likely areas of sediment bypass, accounting for the low sedimentation rates, erosion of paleo-seafloor by ash-rich turbidity currents.

Relatively condensed sections are recognized by the abundant cross-cutting relationships between trace fossils seen in the ichnofabrics, representing the overprinting of multiple successive soft-bottom communities (ichnocoenoses). The fine-grained tuffaceous bed is found to be discontinuous as a result of differential erosion by the turbidite current that deposited the overlying coarse-grained tuff, and locally due to intense bioturbation (Figures 3.10B and 3.11A). The pre-tuff mudstone displays evidence for multiple colonization events, involving repeated cycles of erosion and deposition, followed by slow rates of sedimentation and recolonization. Many of the burrows in the mudstone facies can be categorized as softground "floating" burrows (Droser *et al.*, 2002), such as *Chondrites* and *Teichichnus* where they are recognized in isolation from the fine tuff bed that is inferred to have sourced their burrow fills. The deep tier *Chondrites* and *Teichichnus*, and mid tier *Asterosoma* and *Phycosiphon*, are conspicuous along the lateral profile bed. Shallow tiers are removed by erosion and re-burrowing during vent-bed deposition at the sediment-water interface.

Several tuff-filled burrows including *Asterosoma*, *Chondrites*, *Scolicia*, *Thalassinoides*, *Planolites* and *Teichichnus* are present in the background shelf facies up to 0.6 m below tuff beds, this suggests that either: 1) the open burrows were part of the background facies community and were passively infilled during tuff deposition (e.g. *Thalassinoides, Planolites* and *Chondrites*); or 2) colonization occurred after deposition of the tuff bed and tracemakers burrowed into underlying substrate actively filling their

burrows as they moved through the sediment (e.g. *Asterosoma*, *Scolicia* and *Teichichnus*). In some samples (EC9 and EC10) the central core of *Asterosoma* contain coarse-grained tuff, the associated colonization surface for these burrows are likely to pre-date deposition of the coarse-grained tuff.

The patchiness and rarity of *Thalassinoides* in samples and outcrop suggests that the trace-makers were either: 1) allochthonous organisms were entrained in tuff sediment gravity flows and transported to the outer shelf (Föllmi and Grimm, 1990); or 2) recolonizing the paleo-seafloor post-event bed deposition. The latter is considered more probable, as *Thalassinoides* are recognized in the "background" ichnofabrics.

The burrow-mottled background ichnofabric is cross-cut by several ichnotaxa, this relationship suggests the ichnofabrics do not represent a single ichnocoenosis, or community at any of the localities along strike. The lateral profile beds are condensed and represent successive overprinting of multiple communities or ichnoconoeses. There is strong evidence for time-averaging, with multiple cross-cutting relationships, intense overprinting, and intense bioturbation. Although the time-averaging has not completely removed lithological heterogeneities along the horizontal transect.

Intensely bioturbated outer shelf environments are interpreted as sites of abundant food supply, stable marine salinity, oxygenated water column and pore waters for benthic organisms. Ichnological analysis reveals lateral variability in the ichnofabrics (Figure 3.12). Four ichnofabrics in descending order of abundance: *Asterosoma*-dominated, *Asterosoma-Phycosiphon*, burrow-mottled, and *Teichichnus-Phycosiphon* ichnofabric are recognized in the same bed. The *Cruziana* ichnofacies is present in 12 of 13 samples, with *Skolithos* ichnofacies at a single sample point within the single studied bed.

Bioturbation styles (*sensu* Tonkin *et al.,* 2010; Table 3.1) show little variability between the samples, with sediment mixing, sediment packing, and combination cleaner-packing behaviours being persistent throughout the dataset (Figure 3.12). In addition, low abundance patches of pipe-work trace fossils are present. Rare patches of the pipe-work bioturbation style are directly associated with ichnotaxa from the post-event bed, and are not part of the background sedimentation. Therefore, although both qualitative and quantitative ichnological analyses reveal significant lateral heterogeneity in the ichnological dataset, the net-effect on sedimentary fabrics is generally uniform at the scale of the study presented here.

3.6 Onshore-offshore lateral trends in ichnological variability

In all three case studies there is little change in sedimentology of the studied units on the scale of the lateral profile from 35 m to 60 m in shallow marine settings. However lateral changes in ichnology were found to be variably developed. Maximum variability was found in the offshore shelfal deposits of the Pohutu Formation, characterized by slow continuous deposition in association with event bed deposition. Neslen Formation shoreface and Conway delta plain studies were characterized by relative little lateral change in ichnofabric. Along-strike variability, or patchiness, was found to be un-related to proximity to the paleo-shoreline in the three wave-dominated depositional systems. Instead, the most critical factor appears to be the sediment accumulation style.

Patchiness of the modern seafloor is unlikely to be preserved in the rock record. Modern gradient patterns are comparable to along-dip variability from the onshore to

offshore, and are preserved at a gross-scale in the rock record (Valentine and Jablonski, 2010). The depth-related gradient patterns are a concept on which the archetypal ichnofacies are based upon (Seilacher, 1967). The clustering and mosaic patterns (parallel to the shoreline) on the modern benthic seafloor, a concept on which this study is based cannot be objectively identified due to time averaging and taphonomic processes. The closest analogy of modern seafloor patchiness is a frozen profile bed or frozen tier (Savrda and Bottjer, 1986; Orr, 1994; Taylor *et al.*, 2003), where rapid deposition (e.g. event bed) and minimal erosion has preserved an infaunal community. And, even in such examples (e.g. Utah case study) it is impossible to determine whether the preserved trace fossils reflect a multiple biological communities or a single community.

3.7 Conclusion

The patchy distribution of the modern benthic seafloor is not directly analogous to patterns of spatial ichnological distribution in the rock record. Slow continuous deposition was found to produce complex and highly patchy ichnofabrics, whereas rapid, episodic, event bed deposition was found to be associated with the most uniform development of ichnofabric. Erosion, fluctuation of sedimentation rates and overprinting of successive communities at the sediment-water interface, all introduce geological complexity to ecological patterns – hitherto unexplored. Biological factors of larval dispersal, competition and predation are unlikely to be contributing factors in controlling

the benthic spatial distribution in the rock record due to time-averaging on a geological timescale.

In reservoir characterization studies variability in ichnology and ichnofabrics can be an important control on reservoir quality (e.g., Pemberton and Gingras, 2005; Tonkin *et al.*, 2010). For the petroleum geologist it is commonly the effect of the trace fossil on reservoir quality that is important rather than the ichnotaxonomic identification. The burrowing activity categories of Tonkin *et al.* (2010) are proposed as a practical approach to ichnology for the petroleum geologist undertaking reservoir characterization. The studies of lateral variability presented herein suggest there is inherent ichnotaxonomic variability within most beds, if one considers only the effect on reservoir quality and the style of bioturbation, lateral variability of ichnofabrics/ichnofacies is seen to be less variable than would first appear.

References

Adams, C.J., I.J. Graham, D. Seward, and D.N.B Skinner, 1994, Geochronological and geochemical evolution of late Cenozoic volcanism in the Coromandel Peninsula, New Zealand: New Zealand Journal of Geology and Geophysics, v. 37, p. 359-379.

Anderson, B.G., and M.L. Droser, 1998, Ichnofabrics and geometric configuration of *Ophiomorpha* within a sequence stratigraphic framework: and example from the Upper Cretaceous US western interior: Sedimentology, v. 45, p. 379-396.

Ballance P.F., M.R. Gregory, G.W. Gibson, G.C.H. Chaproniere, A.P. Kadar, and T. Sameshima, 1984, A Late Miocene and Early Pliocene upper slope-to-shelf sequence of calcareous fine sediment from the Pacific margin of New Zealand, *in*, D.A.V. Stow, and D.J.W. Piper, ed., Fine-grained sediments, deep water processes and facies: Geological Society (London) Special Publication 15, Geological Society of London, p. 331-342.

Bednarz, M., and D. McIlroy, 2009, Three-dimensional reconstruction of "phycosiphoniform" burrows: implications for identification of trace fossils in core: Palaeontologica Electronica, v. 12, 15p; http://palaeo-electronica.org/2009_3/195/index.html.

Bennington, J.B., 2003, Transcending Patchiness in the Comparative Analysis of Paleocommunities: A Test Case from the Upper Cretaceous of New Jersey: Palaios, v. 18. p. 22-33.

Beukema, J.J., and J. de Vlas, 1989, Tidal-current transport of thread-drifting postlarval juveniles of the bivalve *Macoma balthica* from the Wadden Sea to the North Sea: Marine Ecology Progress Series, v. 52, p. 193-200.

Bloom, S.A., J.L. Simon, and V.D. Hunter, 1972, Animal-sediment relations and community analysis of a Florida estuary: Marine Biology, v. 13, p. 43-56.

Bromley, R.G., 1996. Trace fossils: biology, taphonomy and applications: London, Chapman and Hall, 361 pp.

Bromley, R.G. and G.K. Petersen, 2008, *Ophiomorpha irregulaire*, Mesozoic trace fossil that is either well understood but rare in outcrop or poorly understood but common in core: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270, p. 295-298.

Carter, L., R.M. Carter, and G.B. Griggs, 1982, Sedimentation in the Conway Trough, a deep near-shore marine basin at the junction of the Alpine transform and Hikurangi subduction plate boundary, New Zealand: Sedimentology, v. 29, p. 475-497.

Cross, T.A., 1986, Tectonic controls of foreland basin subsidence and Laramide style deformation, western United States, *in*, P.A. Allen, and P. Homewood, eds., Foreland basins: International Association of Sedimentologists Special Publication 8, p. 15–40.

Cummins, H., E.N. Powell, R.J. Stanton, and G. Staff, 1986, The rate of taphonomic loss in modern benthic habitats: how much of the potentially preservable community is preserved?: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 52, p. 291-320.

Droser, M.L., S. Jensen, J.G. Gehling, P.M. Myrow, and G.M. Narbonne, 2002, Lowermost Cambrian ichnofabrics from the Chapel Island Formation, Newfoundland: Implications for Cambrian substrates: Palaios, v. 17, p. 3-15.

Dumas, S. and R.W.C. Arnott, 2006, Origin of hummocky and swaley cross-stratification: the controlling influence of unidirectional current strength and aggradation rate: Geology, v. 34, p. 1073-1076.

Ekdale A.A., and D.W. Lewis, 1991, Trace fossils and paleoenvironmental control of ichnofacies in a late Quaternary gravel and loess fan delta complex, New Zealand: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 81, p. 253-279.

Franczyk, K.J., T.D. Fouch, R.C. Johnson, C.M. Molenaar, and W.A. Cobban, 1992, Cretaceous and Tertiary paleogeographic reconstructions for the Uinta-Piceance basin study area: US Geologic Survey Bulletin, v. B-1787-Q, p. 1–37.

Fisher, R.V, 1984, Submarine volcaniclastic rocks, *in,* B.P. Kokelaar, and M.F. Howells, Marginal Basin Geology: Volcanic and associated sedimentary and tectonic processes in modern and ancient marginal basins: Geological Society (London) Special Publication 16, p. 5-27.

Föllmi, K.B., and K.A. Grimm, 1990, Doomed pioneers: Gravity-flow deposition and bioturbation in oxygen-deficient environments: Geology, v. 18, p. 1069-1072.

Fürsich, F.T., and Aberhan, M., 1994, Significance of time averaging for palaeocommunity analysis: Lethaia, v. 23, 143-152.

Garton, M., and McIlroy, D. 2006: A new method for the study of ichnofabric in cryptic highly lithified facies. Journal of Sedimentary Research 76, 1–5.

Gingras, M.K., S.G. Pemberton, C.A. Mendoza, and F. Henk, 1999, Assessing the anisotropic permeability of *Glossifungites* surfaces: Petroleum Geoscience, v. 5, p. 349-357.

Gingras, M.K., B. Macmillan, B.J. Balcom, T. Saunders, and S.G. Pemberton, 2002, Using magnetic resonance imaging and petrographic techniques to understand the textural attributes and porosity distribution in *Macaronichnus*-burrowed sandstone: Journal of Sedimentary Research, v. 72, p. 552-558.

Gingras, M.K., C.A. Mendoza, and S.G. Pemberton, 2004, Fossilized worm burrows influence the resource quality of porous media: AAPG Bulletin, v. 88, p. 875-883.

Gingras, M.K., S.G. Pemberton, S. Dashtgard, and L. Dafoe, 2008, How fast do marine invertebrates burrow?: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270, p. 280–286.

Goldring, R., J.E. Pollard, and A.M. Taylor, 1991, Anconchichnus horizontalis: a pervasive ichnofabric-forming trace fossil in post-Paleozoic offshore siliciclastic facies: Palaios, v. 6, p. 250-263.

Hildebrandt, C., and S. Egenhoff, 2007, Shallow-marine massive sandstone sheets as indicators of palaeoseismic liquefaction; an example from the Ordovician shelf of central Bolivia: Sedimentary Geology, v. 202, p. 581-595.

Howard, J.D., and R.W. Frey, 1975, Regional animal-sediment characteristics of Georgia Estuaries: Senckenbergiana Maritima, v. 7, p. 33-103.

Howard, J.D., and R.W. Frey, 1984, Characteristic trace fossils in nearshore to offshore sequences, Upper Cretaceous of east-central Utah: Canadian Journal of Earth Sciences, v. 21, p. 200-219.

Jerram, D.A., 2001, Visual comparators for degree of grain-size sorting in two and three-dimensions: Computers and Geoscience, v. 27, p. 485-492.

Johnson, R.J., 1970, Variations in diversity with marine benthic communities: The American Naturalist, v. 104, p. 285-300.

Johnson, R.J., 1971, Animal-sediment interactions in shallow water benthic communities: Marine Geology, v. 11, p. 93-104.

Kauffman, E.G., 1984, Paleobiogeography and evolutionary response dynamic in the Cretaceous Western Interior Seaway of North America, *in* G.E.G. Westermann, ed., Jurassic-Cretaceous biochronology and paleogeography of North America: Geological Association of Canada Special Paper 27, p. 273-306.

Kidwell, S.M., and D.W.J. Bosence, 1991, Taphonomy and time-averaging of marine shelly faunas, *in* P.A. Allison, and D.E.G. Briggs, eds., Taphonomy: releasing the data locked in the fossils record: Topics in Geobiology 9, New York, Plenum Press, p. 115-209.

Kidwell, S.M., and K.W. Flessa, 1996, The quality of the fossil record: Populations, species, and communities: Annual Review of Earth and Planetary Sciences, v. 24, p. 433-464.

Kirschbaum, M.A., and R.D. Hettinger, 2004, Facies analysis and sequence stratigraphic framework of Upper Campanian strata (Neslen and Mount Garfield Formations, Bluecastle Tongue of the Castlegate Sandstone, and Mancos Shale), Eastern Book Cliffs, Colorado and Utah: U.S. Geological Survey Digital Data Report, DDS-69-G, 40 pp.

Levinton, J. and B. Kelaher, 2004, Opposing organizing-forces of marine benthic communities: Journal of Experimental Marine Biology and Ecology, v. 300, p. 65-82.

Lewis, D.W., and A.A. Ekdale, 1991, Lithofacies relationships in a late Quaternary gravel and loess fan delta complex, New Zealand: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 81, p. 229-251.

Liu, A.G., D. McIlroy, J.B. Antcliffe, and M.D. Brasier, 2011, Effaced preservation in the Ediacara biota of Avalonia and its implications for the early macrofossil record: Palaeontology, v. 54, p. 607-630.

MacEachern, J.A., M.K. Gingras, K.L Bann, S.G. Pemberton, and L.T. Reich, 2007, Applications of ichnology to high-resolution genetic stratigraphic paradigms, *in*: J.A. MacEachern, S.G. Pemberton, M.K. Gingras, and K.L. Bann, eds., Applied Ichnology: SEPM Core Workshop 52, p. 95–131.

MacEachern, J.A., M.K. Gingras, S.G. Pemberton, and K.L Bann, 2010, Ichnology and Facies Models, *in* N.P James, and R.W. Dalrymple, eds., Facies Models 4: St John's, Geological Association of Canada, p. 19-58.

MacQuaker, J.H.S., and R.L. Gawthorpe, 1993, Mudstone lithofacies in the Kimmeridge Clay Formation, Wessex Basin: implications for the origin and controls on the distribution of mudstones: Journal of Sedimentary Petrology, v. 63, p. 1129–1143.

McConnico, T.S. and K.N., Bassett, 2007, Gravelly Gilbert-type fan delta on the Conway Coast, New Zealand: Foreset depositional processes and clast imbrications: Sedimentary Geology, v. 198, p. 147-166.

McIlroy, D. 2004, A review of ichnological concepts, methodologies, applications and frontiers, *in* D. McIlroy, ed., The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society (London) Special Publication 228, p. 3-27.

McIlroy, D., 2007, Lateral variability in shallow marine ichnofabrics: implications for the ichnofabric analysis method: Journal of the Geological Society of London, v. 164, p. 359-369.

McIlroy, D., 2008, Ichnological analysis: The common ground between ichnofacies workers and ichnofabric analysts: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270, p. 332-338.

McIlroy, D., N.S. Tonkin, C. Phillips, and L.G. Herringshaw, 2009, Comment on "*Ophiomorpha irregulaire*, Mesozoic trace fossil that is either well understood but rare in outcrop or poorly understood but common in core" by R.G. Bromley and G.K. Pedersen: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 284, p. 392-395.

McIlroy, D., and M. Garton, 2010, Realistic interpretation of ichnofabrics and palaeoecology of the pipe-rock biotope: Lethaia, v. 43, p. 420-426.

Martin, M. A., and J. E. Pollard, 1996, The role of trace fossil (ichnofabric) analysis in the development of depositional models for the Upper Jurassic Fulmar Formation of the Kittiwake Field (Quadrant 21 UKCS), *in* A. Hurst, H. D. Johnson, S. D. Burley, A. C. Canham, and D. S. Mackertich, eds., Geology of the Humber Group: Central Graben and Moray Firth, UKCS: Geological Society (London) Special Publication 114, p. 163-183.

Mazengarb, C, D. A. Francis, and P. R. Moore, 1991, Sheet Y16—Tauwhareparae, Geological map of New Zealand, scale 1:50 000: Lower Hutt, New Zealand, Department of Scientific and Industrial Research.

Middleton, G.V., 1973, Johannes Walther's law of the correlation of facies: GSA Bulletin, v. 84, p. 979-988.

Orr, P.J., 1994, Trace fossil tiering within event beds and preservation of frozen profiles: and example from the Lower Carboniferous of Menorca: Palaios, v.9, p. 202-210.

Ota, Y., T. Yoshikawa, N. Iso, A. Okada, and N. Yonekura, 1984, Marine terraces of the ConwayCoast, South Island, New Zealand: New Zealand Journal of Geology and Geophysics, v. 27, p. 313- 325.

Owen, G., 1996, Experimental soft-sediment deformation; structures formed by the liquefaction of unconsolidated sands and some ancient examples: Sedimentology, v. 43, p. 279-293.

Pattison, S.A.J., H. Williams, and P. Davies, 2007, Clastic sedimentology, sedimentary architecture, and sequence stratigraphy of fluvio-deltaic, shoreface, and shelf deposits, Upper Cretaceous, Book Cliffs, eastern Utah and western Colorado, *in*, R.G.H. Raynolds, ed., Roaming the Rocky Mountains and Environs: Geological Field Trips: Geological Society of America Field Trip Guide 10, p. 17-43.

Pemberton, S.G., and R.W. Frey, 1984, Quantitative methods in ichnology: spatial distribution among populations: Lethaia, v. 17, p. 33–49.

Pemberton, S. G., and M. K. Gingras, 2005, Classification and characterizations of biogenically enhanced permeability: AAPG Bulletin, v. 89, p. 1493-1517.

Pemberton, S.G., and J.A. MacEachern, 1995, The sequence stratigraphic significance of trace fossils: examples from the cretaceous Foreland Basin of Alberta, Canada, *in*, J.A. Van Wagoner, and G.T. Bertram, eds., Sequence Stratigraphy of Foreland Basin Deposits - Outcrop and Subsurface Examples from the Cretaceous of North America: American Association of Petroleum Geologists Memoir 64, p. 429-475.

Reise, K., 1979, Spatial configurations generated by motile benthic polychaetes: Helgoland Marine Research, v. 32, p. 55-72.

Savrda, C.E., and D.J. Bottjer, 1986, Trace-fossil model for reconstruction of paleo-oxygenation in bottom bottom waters: Geology, v. 14, p. 3-6.

Seilacher, A., 1967a, Bathymetry of trace fossils: Marine Geology, v. 5, p. 413-428.

Shanks, A.L., 2002, The abundance, vertical flux, and still-water and apparent sinking rates of marine snow in a shallow coastal water column: Continental Shelf Research, v. 22, p. 2045–2064.

Shane, P., T. Black, S. Eggins, and J. Westgate, 1998, Late Miocene marine tephra beds: recorders of rhyolitic volcanism in North Island, New Zealand: New Zealand Journal of Geology and Geophysics, 1998, v. 41, p.165-178.

Stagpoole, V., B. Field, R. Sutherland, C.I. Uruski, and K. Zink, 2008, Petroleum prospectivity of the Raukumara Basin, New Zealand, *in*, GNS Science Consultancy Report 2008/111, New Zealand Open-file Petroleum Report 3921: Crown Minerals, Wellington, 80 p.

Swift, D.J.P., P.M. Hudelson, R.L. Brenner, and P. Thompson, 1987, Shelf construction in a foreland basin: storm beds, shelf sandbodies, and shelf-slope depositional

sequences in the Upper Cretaceous Mesaverde Group, Book Cliffs, Utah: Sedimentology v. 34, p. 423–457.

Swift, D.J.P., and J.A. Thorne, 1991, Sedimentation on continental margins, I: a general model for shelf sedimentation, *in* Swift, D.J.P., Oertel, G.F., Tillman, R.W., and Thorne, J.A., eds., Shelf Sand and Sandstone Bodies: International Association of Sedimentologists, Special Publication 14, p. 3–31.

Taylor, A.M., and R., Goldring, 1993, Description and analysis of bioturbation and ichnofabric: Journal of the Geological Society of London, v. 150, p. 141-148.

Taylor, A.M., R. Goldring, and S. Gowland, 2003, Analysis and application of ichnofabrics: Earth-Science Reviews, v. 60, p. 227-259.

Thorson, G., 1950, Some factors influencing the recruitment and establishment of marine benthic communities: Netherlands Journal of Sea Research, v. 3, p. 267-293.

Tilman, D., C.L. Lehman, and P. Kareiva, 1997, Population dynamics in spatial habitats: *in* D. Tilman, and P. Kareiva, eds., Spatial Ecology, The Role of Space in Population Dynamics and Interspecific Interactions: Monographs in Population Biology 30, p. 3-20.

Tonkin, N.S., D. McIlroy, R. Meyer, and A. Moore-Turpin, 2010, Bioturbation influence on reservoir quality: A case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada: AAPG Bulletin, v. 94, p. 1059-1078.

Uruski, C.I., C. Kennedy, V. Stagpoole, R. Sutherland, and S. Henrys, 2008, The discovery of a new sedimentary basin: Offshore Raukumara, East Coast, North Island, New Zealand: APPEA Journal, v. 48, p. 53-68.

Valentine, J.W., and D. Jablonski, 1993, Fossil communities: Compositional variation at many time scales, *in,* R.E. Ricklefs and D. Schluter, eds., Species diversity in ecological communities: historical and geographical perspectives: University of Chicago Press, p. 341-349.

Valentine, J.W., and D. Jablonski, 2010, Origins of marine patterns on biodiversity: some correlates and applications: Palaeontology, v. 53, p. 1203-1210.

Van Wagoner, J.C., 1995, Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book cliffs, Utah, USA. *in* J.C. Van Wagoner, and G.T. Bertram, eds., Sequence Stratigraphy of Foreland Basin Deposits: American Association of Petroleum Geologists Memoir 64, Tulsa, p. 137–256.

Van Wagoner, J.C., R.M. Mitchum, K.M. Campion, and V.D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high resolution correlation of time and facies: Tulsa, AAPG Methods in Exploration Series 7, 55pp.

Wetzel, A., and R.G. Bromley, 1994, *Phycosiphon incertum* revisited: *Anconichnus horizontalis* is its junior subjective synonym: Journal of Paleonotology, v. 68, p. 1396-1402.

Willis, A., 2000, Tectonic control of nested sequence architecture in the Sego Sandstone, Neslen Formation and Upper Castlegate Sandstone (Upper Cretaceous), Sevier Foreland Basin, Utah, USA: Sedimentary Geology, v. 136, p. 277-317.

Woodin, S.A., 1976, Adult-larval interactions in dense infaunal assemblages: patterns of abundance: Journal of Marine Research, v. 34, p. 25-41.

Chapter 4: Bioturbated key stratigraphic surfaces and their autocyclic and allocyclic interpretations

Abstract

Trace fossils are common at key stratigraphic surfaces (both erosional and non-depositional) reflecting their common association with parasequence boundaries in many petroleum reservoir intervals and in a wide range of marine facies. The most common of these trace fossils is perhaps *Thalassinoides*, which are easily identified in both core and in outcrop, and colonize a variety of substrates including softgrounds and firmgrounds. This large, unlined branched burrow often forms deep-tier box-works and/or galleries that are conspicuous within the substrate, and can form conduits for flow of hydrocarbons. Four idealized taphonomic expressions of *Thalassinoides* are considered in terms of possible autocylic and allocyclic causative mechanisms: 1) coarse-grained burrow fill in fine-grained sediment (e.g., mudstone: sandstone); 2) fine-grained burrow fill in fine-grained sediment (e.g., mudstone: mudstone); 3) fine-grained burrow fill in coarse-grained sediment (e.g., sandstone: mudstone); 4) coarse-grained burrow fill in coarse-grained sediment (e.g., sandstone: sandstone). With careful ichnological investigation, realistic paleoenvironmental interpretations should be considered to assess the relative merit of integration of both autocyclic and allocyclic processes for trace fossil-bearing surfaces of sequence stratigraphic significance.

4.1 Introduction

A key sequence stratigraphic surface is a sedimentary surface that characterizes a hiatus produced by erosion or non-deposition (Mitchum *et al.*, 1977; Van Wagoner *et al.*, 1990). Erosion and non-deposition can be caused by either allocyclic or autocyclic mechanisms. Distinguishing between basin-wide and local environmental processes is integral to sequence stratigraphic analyses (Einsele *et al.*, 1991; Catuneanu, 2006; Tomer, *et al.*, 2011). Sequence stratigraphic surfaces are interpreted as the products of allocyclic mechanisms, and are associated with basin-wide to global changes in relative sea-level change. These basin-wide changes are can be caused by an interplay between changes in rates of eustatic sea-level change, sedimentation rates, and tectonically induced subsidence or uplift. The relative importance of these processes are related to accommodation space gain or loss for sediment accumulation (Mitchum *et al.*, 1977; Van Wagoner *et al.*, 1988; Van Wagoner *et al.*, 1990).

Ichnological analysis enables interpretations of an autocyclic origin, a process that occurs within an evolving sedimentary basin without any external (eustatic) forcing; or an allocyclic origin, a process influenced by events external to the basin including changes in global climate, tectonism and eustasy (Einsele *et al.*, 1991). Shallow marine deposition of sandstone or mudstone is a component of transgressive, or regressive parasequence sets; and associated with: 1) aggradation; 2) progradation; or 3) retrogradation. Key sequence stratigraphic surfaces with distinctive ichnological expressions include the

transgressive surface of erosion (TSE), sequence boundary (SB), flooding surface (FS) or amalgamated surface (SB/TS).

Stratigraphic surfaces in bioturbated successions are commonly identifiable where there is some combination of distinct facies change, variation (usually an anomalous increase) in bioturbation intensity, unexpected trace fossil cross-cutting relationships, and lithologic contrast in burrow fill relative to the host sediment. Even where there is low lithologic contrast or subtle facies changes, bioturbated stratigraphic surfaces may be expressed as overprinting ichnofabrics. Key sequence stratigraphic surfaces have allocyclic, autocyclic or ecological significance and can be fundamental in the identification of system tracts, and thus ichnological expressions (Einsele *et al.*, 1991; Catuneanu *et al.*, 2009; Dalrymple, 2010; Figure 4.1).

Key sequence stratigraphic surfaces of relative sea-level change may involve erosion, non-deposition or condensation, and in marine settings commonly have distinctive ichnological expressions (Figure 4.2). Ichnology can provide aids in the recognition of such surfaces in marine environments in several ways by providing evidence for:

1) Significant paleoenvironmental change reflected in marked ichnological assemblage change across or associated with a single stratigraphic surface.

2) Stratigraphic condensation, which may be inferred from the presence of anomalously intense bioturbation intensities (often with an associated facies shift) In regions of very slow sedimentation. Overprinting of infaunal communities

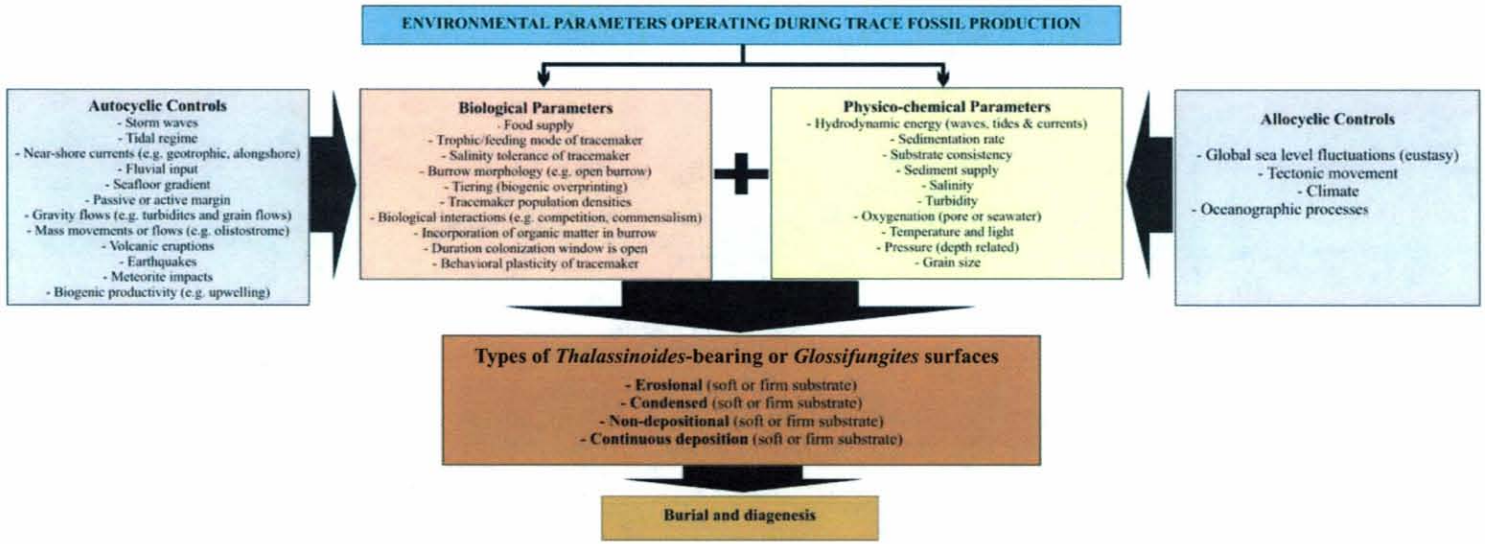


Figure 4.1. Summary diagram of environmental parameters and auto/allocyclic controls governing production and taphonomy of trace fossils. Autocyclic and and allocyclic controls act upon both biological and physico-chemical parameters. The different taphonomic expressions of *Thalassinoides* enable depositional history, and environmental information to be interpreted, including recognition of key sequence stratigraphic surfaces.

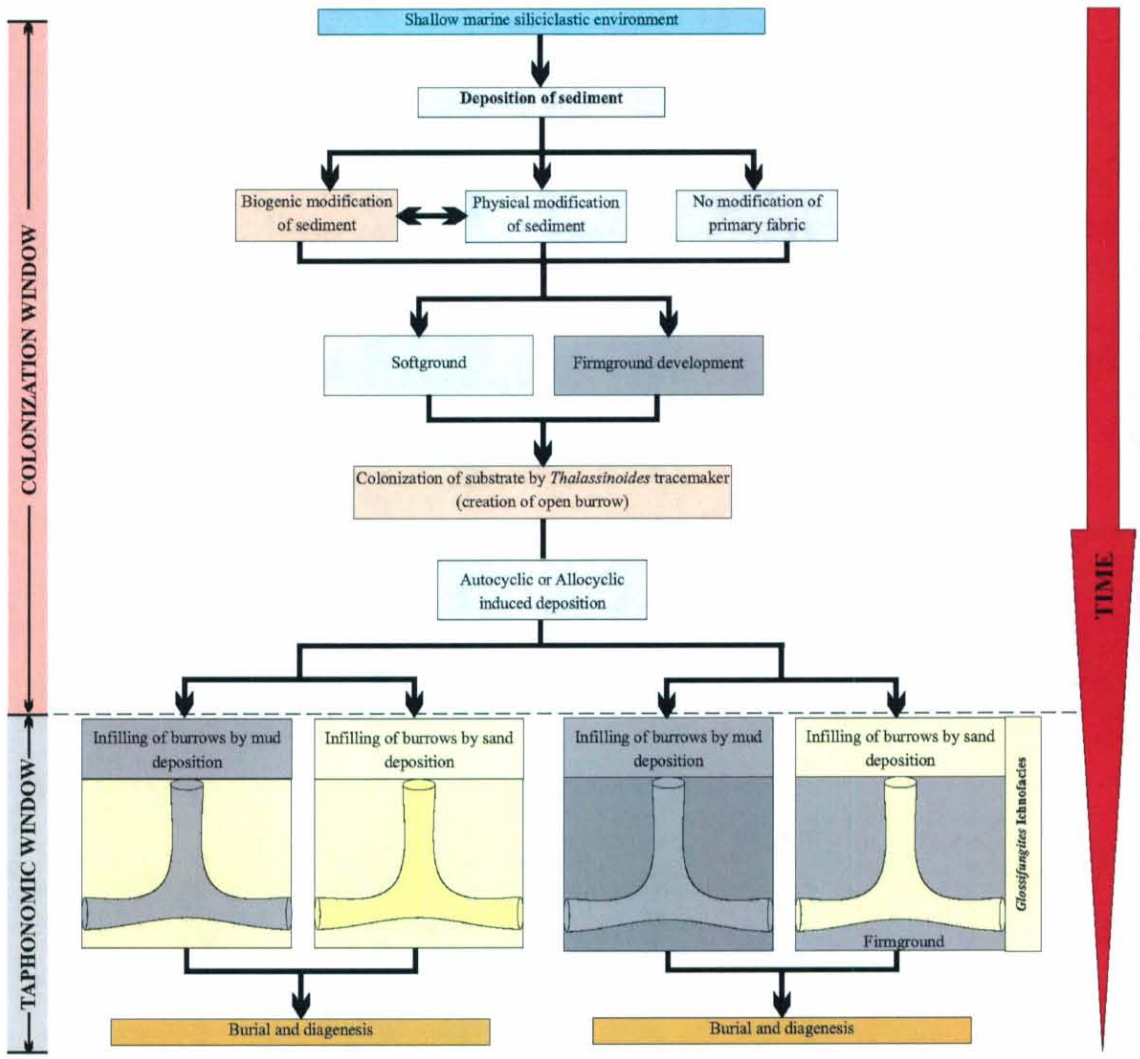


Figure 4.2. Taphonomy of *Thalassinoides* burrows. Idealized flow diagram of creation and preservation of *Thalassinoides* burrows in a siliciclastic heterolithic shallow marine environment. Four taphonomic expressions of *Thalassinoides* in siliciclastic rocks are described above, the two most conspicuous are sandstone-filled burrows in mudstone, and mudstone-filled burrows in sandstone. The more subtle expressions are sandstone filled burrows in sandstone and mudstone-filled burrows in mudstone. In addition, preservation can be enhanced or obscured by diagenesis (see Gingras *et al.*, 2007).

related to gradually changing (often deepening) paleoenvironments (ichnological cross-cutting relationships).

3) Partially lithified sediments on the seafloor evidenced by the presence of firmground *Glossifungites* ichnofacies trace fossils or borings into fully lithified carbonate substrates (*Trypanites* ichnofacies). Lithification may either be caused by seafloor cementation or erosional exhumation of lithified sediment (caused by erosion induced by relative sea-level change).

Ecological studies are, by necessity, performed on biological timescales, considering census populations of organisms, not burrows (e.g., Swinbanks and Luternauer, 1987. Inherent in any analysis of ancient ecosystems is the possibility for time averaging of assemblages of fossils (Kidwell and Bosence, 1991; Valentine and Jablonski, 1993; Fürsich and Aberhan, 1994). The same is true of trace fossils. It is difficult to determine whether an assemblage of body or trace fossils represents the activities of a true biological community (Cummins *et al.*, 1986; Kidwell and Flessa, 1996; McIlroy, 2008; McIlroy and Garton, 2010). Thus, it is unlikely a trace fossil assemblage represents a coenosis in the strict sense of the term (see discussion of ichnocoenosis in McIlroy, 2004a), rather it is the preservation of a number of communities that are superimposed (e.g., multiple ichnocoenoses). The most commonly cited example of a ichnological assemblage at a bioturbated key stratigraphic surface is the firmground *Glossifungites* ichnofacies, commonly associated with a parasequence boundary or transgressive surface of erosion (e.g., MacEachern and Pemberton, 1992; Taylor and Gawthorpe, 1993; Savrda *et al.*, 2001; Gingras *et al.*, 2002).

Thalassinoides is the trace fossil most commonly recognized in association with the *Glossifungites* ichnofacies (Table 4.1). *Thalassinoides* is also a component of the *Cruziana*, *Zoophycos* and *Nereites*, and *Teredolites* ichnofacies (Frey *et al.*, 1990). *Thalassinoides* is easily recognizable in core, and is common in shallow marine strata from the Triassic onwards (Table 4.1 and Table 4.2). Recent work has recognized that the classical expression of the *Glossifungites* ichnofacies as firmground burrows cut into bioturbated mudstones can also express autocyclic processes associated with colonization of erosional channel floors, and in association with tidal flat firmgrounds (McIlroy, 2004b). In modern estuarine firmgrounds, *Thalassinoides* at "*Glossifungites* surfaces" are attributed to both autocyclic and allocyclic mechanims (Gingras *et al.*, 2001, 2004). Firmground ichnotaxa (*Glossifungites* ichnofacies) include *Skolithos*, *Diplocraterion*, *Chondrites*, *Palaeophycus*, *Psilonichnus* and *Zoophycos* (MacEachern *et al.*, 2007a). "*Glossifungites* surfaces" as they have been dubbed in the literature, may enhance the porosity and permeability characteristics of a reservoir by increasing vertical permeability (e.g., Gingras *et al.*, 1999; Pemberton and Gingras, 2005; Cunningham *et al.*, 2009; Tonkin *et al.*, 2010).

The trace makers of *Thalassinoides* are commonly considered to be various species of callianassid crustaceans (Swinbanks and Luternauer, 1987; Table 4.1). These shrimps employ a range of burrowing behaviours in mudstone and sandstone facies (Ziebis *et al.*, 1996; Yang *et al*, 2009; Table 4.1). Callianassid shrimps produce extensive bedding-parallel galleries connected to the sediment water interface by shafts (Swinbanks and Luternauer, 1987). The depth of bioturbation of callianassids and ancient *Thalassinoides* is variable, and is commonly substrate dependent (e.g., Griffis and

Taphonomy of *Thalassinoides*	Depositional Environment	Key Surface Interpreted	Age	References
Mudstone/fine-grained filled in sandstone host sediment	Bay margin, brackish-water to marine, lignite-fill in sand.	Transgressive surface of erosion (TSE, *Glossifungites*)	Pebas Fm Miocene	Gingras et al., 2002.
	Backshore tidal channel.	Tidal channel erosion (*Teredolites*).	Modern	MacEachern et al., 2007a.
Sandstone/coarse-grained filled in mudstone host sediment (classic "*Glossifungites* surface")	Fluvio-deltaic succession.	Transgressive surface of erosion (TSE), wave ravinement surface, transgressive lag (*Glossifungites*).	Rio Bonito Fm Permian	Buatois et al., 2007.
	Deltaic.	Sequence boundary (*Glossifungites*).	Freitag Fm Permian	Fielding et al., 2007.
	Bay margin, brackish-water to marine, shell/sandstone-filled in lignite/mudstone.	Regressive surface of erosion (TSE, *Glossifungites*)	Pebas Fm Miocene	Gingras et al., 2002.
	Shelf, coarse sandstone-fill in sandstone.	TSE (*Glossifungites*).	Sag River Fm Triassic	Pemberton & Gingras, 2005.
	Coastal plain, sandstone in mudstone.	Basin-wide unconformity (*Glossifungites*).	Mirador Fm Eocene	Pemberton & Gingras, 2005.
	Basin, sandstone/grainstone in mudstone	Event and paleo-oxygentation indicators.	San Gregraio Fm Oligio-Miocene	Grimm & Follmi 1994
	Tidal embayment, shell-hash-fill.	Base of parasequence.	Punta Judas Fm Miocene	Kraywinkel & Seyfried, 1996.
	Shoreface, sandstone-fill in mudstone.	Several examples from core, base of incised valley system, sequence boundary/flooding surfaces (*Glossifungites*).	Viking Fm Cretaceous	Pemberton & MacEachern, 1995; MacEachern & Burton, 2000.
	Lower offshore, pebble-filled in mudstone	SB overlain by forced regressive shore or high-energy FS/SB overlain by a stillstand shoreface (*Glossifungites*).	Cardium Fm Cretaceous	Pemberton & MacEachern, 1995.
	Backshore, tidal channel, sand-filled in coal seam	Tidal channel erosion, base level rise in marginal marine environments (woodground *Thalassinoides*, *Teredolites*).	Modern	MacEachern et al., 2007a
	Marginal marine, channel, delta and lagoonal facies, sand-filled in coal seam or carbonaceous-rich siltstone.	Base of channels at erosional contact with coal and channel fill sandstones.	Blackhawk Fm Cretaceous	Kamola, 1984.
	Offshore transition zone, shell debris and serpulid worm cast fill in sandstone.	Marine flooding surface, omission surface, firmground to hardground development.	Ula & Farsuud Fm Jurassic	Taylor & Gawthorpe, 1993.
	Sandstone (estuarine) in marlstone (offshore shelf).	Sequence boundary, transgressive ravinement associated with K-T boundary, development of firmground.	Clayton Sands K-T boundary	Savrda, 1993.
	Submarine bank, coarse sand/pebble-fill.	Firmground at sequence boundary, lowstand erosion at submarine bank-top setting.	Miocene Monterey Fm	Savrda, 1995.
	Passive margin shelf, clinoform-toe, Type 2 sandstone/pebble in mudstone.	Firmground (deep water *Glossifungites*) development indicates erosional exhumation of compacted sediments, transgression induced sediment starvation.	Eocene-Pliocene ODP Site 1073	Savrda et al., 2001.
Sandstone in sandstone	Slope.	Total organic carbon (TOC) poor and low sedimentation rates.	Late Quaternary	Lowemark et al., 2004.
Mudstone/fine-grained in mudstone	Passive margin shelf clinoform-toe, Type 1 mudstone in mudstone.	Softground, glaucontic sand-rich intervals.	Eocene-Pliocene ODP Site 1073	Savrda et al., 2001.
Carbonates	Sucrosic dolomite in micritic calcite.	Ravinement bed developed on regional TSE (*Glossifungites*).	Arab-D Fm Jurassic	Pemberton & Gingras, 2005.
	Pelagic, white chalk nodules in darker marl	Differential cementation, early diagenesis, non-deposition.	Cretaceous	Bromley, 1967.
	Sandy marlstone-fill in sandy chalk.	Firmground, sequence boundary/transgressive co-planar surface.	Cretaceous-Paleocene	Savrda, 2007.
	Outer shelf, chalk-fill in marl and marlstone-fill in chalk.	Bed-junction preservation, sedimentation rate change, clastic dilution mechanism for carbonate cyclicity.	Demopolis Chalk Cretaceous	Locklair & Savrda, 1998.
	Various chalk.	Omission surfaces, discontinuity surfaces, hardgrounds.	Cretaceous Eocene, Tertiary European Chalks	Bromley, 1975.
	Shelf, micrite in micrite, Dolostone-fill in micrite.	Firmgrounds, preferential burrow fill dolomitization, no physical or biogenic introduction of different grain size.	Manitou Fm Lower Paleozoic, Cambrian to Ordivician	Myrow, 1995.
Diagenetic enhancement	Deltaic, thickened by concretionary growth.	Sequence boundary (SB).	Punta Judas Fm Miocene	Kraywinkel & Seyfried, 1996.

Table 4.2. *Thalassinoides* occurrence in ancient & modern siliciclastic and carbonate environments.

Modern *Thalassinoides* tracemaker	Environment	Burrow Morphology	Significance	References
Callianassa truncata, mud shrimp	Shallow bay, 2-15m water depth. Giglio Island, Italy, Mediterranean Sea.	Fine to coarse sand. Conical mound (exhalant) and funnel-shaped depressions (inhalants) at surface. 80cm sediment depth, galleries with chambers.	Complex burrow networks and functional burrow morphology changes the geochemical character of the substrate. Bio-pumping of dissolved oxygen down to 60-80cm, accelerates organic matter degradation. Oxic sediment surrounds burrows of 12-25mm diameter.	Ziebis *et al.*, 1996.
Callianassa californiensis and *Callianassa gaga*, ghost shrimp.	Soft-bottom intertidal sand and mud flats, tidal height maximum is 3m, Bahia de San Quintin, Baja California, Mexico.	Sand burrow sediment depth is 45cm. Mud burrow sediment depth is 25cm. Galleries with chambers.	Sediment type (sand vs mud) influences burrow morphology.	Griffis and Chavez, 1988.
Neotrypaea californiensis, ghost shrimp.	Tidal channel margin. Mugu Lagoon, California, USA.	Sand. Predominantly vertical galleries with chambers, but extensive maze horizontally-oriented systems at artificial glass plate barriers.	Modern thalassinidean shrimp respond to barriers by modifying the burrow architecture, or by finding a way around or through the barrier. Analogy can be applied to bioclastic barriers or buried firmgrounds in the rock record.	Miller and Curran, 2001.
Callianassa californiensis, ghost shrimp.	Tidal flat, Fraser Delta, BC, Canada.	Mud to sand. Predominantly horizontal galleries with chambers, and surficial mounds. *C. californiensis* extrudes 18 +/- 9 ml of wet sediment/shrimp/day onto the substrate surface.	Distribution on tidal flats not influenced by textural sediment properties. Although lowered burrow intensity in eelgrass root mats.	Swinbanks and Luternauer, 1987.
Neotrypaea californiensis, ghost shrimp.	Swash bars, macrotidal flats, Dongho, Baeksu and Doowoo, southwestern coast of Korea. Tidal height of 6m.	Firmground muds. Open, unlined burrows, dominated by *Psilonichnus* and *Thalassinoides* that cross-cut softground suites of *Skolithos*, *Arenicolites* and *Monocraterion*. Mud only needs to be buried as little as 0.5 m for a few years to produce the firmground muds.	*Glossifungites* ichnofacies of *Psilonichnus*- and *Thalassinoides*-like burrows is associated with autogenic migration of the swash bars, rather than allogenic processes such as transgressive ravinement.	Yang *et al.*, 2009.
Upogebia stellata and *U. deltaura*, mud shrimp.	Soft-bottom, nearshore. 7-10m water depth. Plymouth Sound, North Sea and Isle of Cumbrae, UK.	Galleries with chambers, 12-23mm diameter, 7-24cm sediment depth. Surface openings constricted.	Burrow irrigation by pleopod beating, which draws oxygenated water into the burrow and also particulate food for suspension feeding	Astall *et al.*, 1997.
Upogebia pugettenis, mud shrimp.	Mesotidal estuary, subtidal to intertidal, tidal range 2-3m, Willipa Bay, Washington, USA.	Softground to firmground muds, vertically oriented, 9-21mm diameter, sediment depth 40-60cm (unknown maximum depth in firmground).	*Upogebia* not observed in substrates firmer than $1x10^9$ Pa. Burrow morphology does not change from soft to firm substrate.	Gingras *et al.*, 2001.
Upogebia pugettenis, mud shrimp.	Mesotidal estuary, intertidal, tidal range 2-3m, Willipa Bay, Washington, USA.	Firmground mud and woodground with *Thalassinoides*-like borings. 24mm diameter	Rare *Thalassinoides*-like borings in *Terodolites* ichnofacies (woodground) not previously recognized. Burrow morphology does not change from soft to firm substrate. Transgressive surfaces may be demarcated not only by the *Teredolites* and *Glossifungites* ichnofacies, but also by coeval softground assemblages	Gingras *et al.*, 2004.

Table 4.1. Table of modern analogues of the *Thalassinoides* tracemaker.

Chavez, 1988; Gingras *et al.*, 2001). *Thalassinoides* is usually associated with intense hydrodynamic currents (Frey and Seilacher, 1980; Kamola, 1984; Gowland, 1996; Gingras *et al.*, 1998; Buatois *et al.*, 2007), and as such it is commonly filled with coarse-grained sediment post-mortem (or post-abandonment), to form the classical "*Glossifungites*-type" expression of the trace fossil (MacEachern *et al.*, 2007a; Figure 4.2). The coarse-grained infill of the *Thalassinoides* is commonly used to help recognize a significant change in hydrodynamic regime (Wanless *et al*, 1988). In many cases, that change in hydrodynamic regime has been inferred to be associated with relative sea-level change (Savrda *et al.*, 2001; Gingras *et al.*, 2002; MacEachern *et al.*, 2007b). Relative sea-level change is not the only possible cause of the "*Glossifungites* type" preservation of *Thalassinoides*, and valid autocyclic interpretations can also be drawn from a given stratigraphic surface.

This work explores the preservation of *Thalassinoides* as an example of a common *Glossifungites* ichnofacies trace fossil, and objectively assesses the fundamental ichnological and hydrodynamic processes responsible for them. A conceptual model to encompass the main expressions of *Thalassinoides* preservation in sandstones and mudstones, characterizing the burrow fill with respect to the host sediment, is developed herein. The possible modes of preservation are:

1) Coarse-grained burrow fill in fine-grained sediment (e.g., mudstone: sandstone; Figure 4.3A).

2) Fine-grained burrow fill in fine-grained sediment (e.g., mudstone: mudstone; Figure 4.3B).

3) Fine-grained burrow fill in coarse-grained sediment (e.g., sandstone: mudstone; Figure 4.3C).

4) Coarse-grained burrow fill in coarse-grained sediment (e.g., sandstone: sandstone; Figure 4.3D).

Examples of the four taphonomic expressions of *Thalassinoides* have been studied both in outcrop and core. Ichnofabric analysis is used in this study to assess changes in depositional setting and paleoecology associated with the different taphonomic expressions of *Thalassinoides* (see reviews in Taylor *et al.*, 2003; McIlroy, 2004a, 2008; Gingras *et al.*, 2007). The ichnofabric method allows easy comparison of ichnofabrics from different geographic successions, recognition of sequence stratigraphic context, interpretation of community development (e.g., cross-cutting relationships and tiering) and consequent changes in community structure. This study recognizes the following stages of formation of *Thalassinoides* ichnofabrics: 1) deposition of the host sediment; 2) colonization of substrate by *Thalassinoides*-making organism; 3) infilling of burrow and deposition of the casting medium; and 4) burial and diagenesis (Figure 4.2). These fundamental components of the formation of *Thalassinoides* ichnofabrics are influenced by a combination of ecological, and sedimentological processes. The sedimentological processes may be either autocyclically or allocyclically controlled. The challenge for the petroleum geologist and ichnologist is determining whether the resultant ichnofabric is of sequence stratigraphic importance or whether normal autocyclic processes can account for the observed relationships. This research builds on previous work on trace fossils as key sequence stratigraphic surface indicators (Pemberton *et al.*, 1992; Bromley 1996;

Taylor and Gawthorpe, 1993; Gowland, 1996; Gingras *et al.*, 2002, 2008; Taylor *et al.*, 2003; McIlroy, 2004b; MacEachern *et al.*, 2007b).

This study focuses on *Thalassinoides* due to its abundance in the rock record, and its pipe-work bioturbation style (cf. Tonkin *et al.*, 2010 and Chapter 2). It is important to recognize that not all bioturbated surfaces or *Glossifungites* surfaces have sequence stratigraphic significance. This research proposes autocyclic alternatives that may occur more commonly in the rock record as part of the evolution of a sedimentary basin. Published literature and case studies are used as examples of *Thalassinoides*-bearing stratigraphic surfaces, with the aim to provide both alternative autocyclic and allocyclic mechanisms to produce the same taphonomic outcome. Modern analogues (Table 4.1) and ancient examples (Table 4.2) are discussed in detail to demonstrate the multiple pathways (autocyclic and allocyclic) that lead to formation of a particular preservation of *Thalassinoides* (Figure 4.2). The overall objective of this study is to define the validity of using *Thalassinoides* as a indicator for key stratigraphic surfaces, and outline all applicable autocyclic and allocyclic processes (Figure 4.2).

4.2 Modern analogues for *Thalassinoides*

Through the study of modern marine environments and aquaria experiments it is now recognized that the trace-making organism of *Thalassinoides* is most likely a thalassinid shrimp (e.g., Swinbanks and Luternauer, 1987; Miller and Curran, 2001; Table 4.1). Many modern species of burrowing crustaceans produce *Ophiomorpha*-and

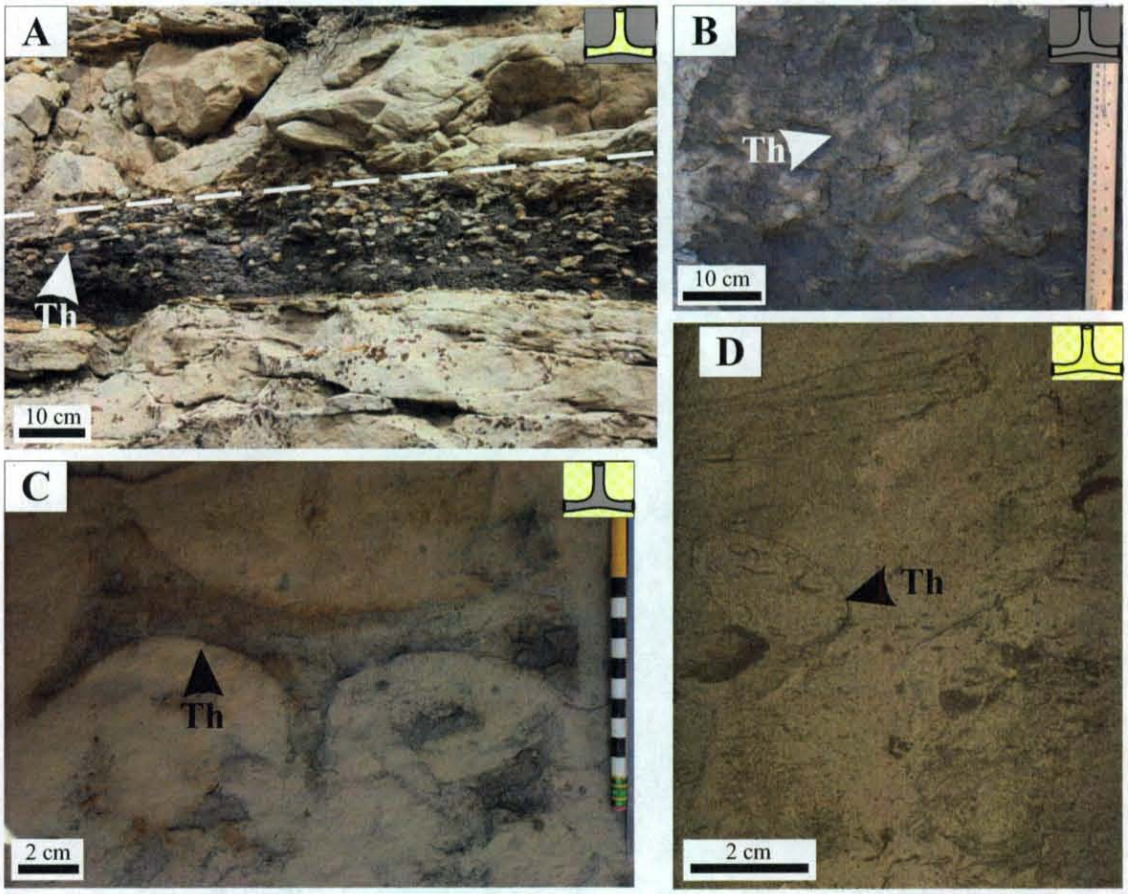


Figure 4.3. Four taphonomic expressions of *Thalassinoides* in marine siliciclastic shallow marine environments. Example A from Blackhawk Formation, Book Cliffs, Utah. Examples B and C from Lajas Formation, Neuquén Basin, Argentina. Example D is core from Ben Nevis Formation, Hebron Field, offshore Newfoundland. **(A)** *Thalassinoides* sandstone-filled burrows in carbonaceous mud in marginal marine environment. This *Glossifungites* surface can be interpreted as a sequence boundary (SB), firmground was exhumed by channel erosion and colonized during transgression. The alternate autocyclic interpretation is a concealed firmground. **(B)** *Thalassinoides* mudstone-filled burrows in mudstone in distal delta front facies, note the subtle taphonomic expression. Ichnofabric is interpreted as oxygenated distal delta front setting. Bioturbation intensity is high implying slow continuous deposition, where rate of bioturbation is greater than rate of sedimentation in softground paleoenvironment (ruler for scale in 10 mm intervals). **(C)** *Thalassinoides* mudstone-filled burrow in sandstone, indicates a hiatal surface between two shallowing/coarsening upward cycles in the delta front. The change in sediment delivery is generated by autocyclic delta lobe switching and abandonment/subsidence (scale bar in 10mm intervals). **(D)** *Thalassinoides* sandstone filled burrows in sandstone from core, note very subtle taphonomic expression. Ichnofabric is interpreted as oxygenated lower shoreface setting. Intense bioturbation and overprinting indicate erosive storm-induced event bed deposition in this softground paleoenvironment.

Thalassinoides-like burrows (Pryor, 1975; Swinbanks and Luternauer, 1987). Thalassinidean decapods including the mud shrimp *Upogebia*, the ghost shrimp *Neotrypaea californiensis* (formerly *Callianassa californiensis,* Table 4.1), as well as fiddler crabs create burrows somewhat analogous to *Thalassinoides* in modern soft substrates (Griffis and Suchanek, 1991; Gingras *et al.*, 2001). Freshwater crayfish (parastacids) are also possible progenitors of *Thalassinoides* (Martin *et al.*, 2008).

Modern thalassinid shrimps construct burrows that resemble *Thalassinoides* trace fossils with vertical shafts, and horizontal to oblique galleries at depths to 1 m deep (Swinbanks and Luternauer, 1987; Table 4.1). The burrows are kept clear of detrital sediment during the life of the burrowing organism by active manipulation of grains, and excavation of material back to the sediment-water interface by organism-induced water currents (Sheehan and Schiefelbein, 1984; Swinbanks and Luternauer, 1987). This process of excavation using the limbs of the crustacean can, in firmground sediments, leave scratch marks (bioglyphs) which have been named *Spongeliomorpha* by some authors (Bromley and Frey, 1974; Gibert and Robles, 2005), but synonymised with *Thalassinoides* by others (Fürsich, 1973; Schlirf, 2000). In vertical cross-section the bioglyph cannot be seen and recognition of a firmground expression is commonly based on a lack of compression of the burrow. The host mudstone is inferred to have already dewatered and, as such, will not significantly compress during subsequent burial.

Research on the ecology of thalassinid shrimps in modern soft substrate environments describe these crustaceans as dietary/trophic generalists or exhibiting a range of feeding behaviours, and cannot be considered exclusively as deposit feeders (Griffis and Chevez, 1988; Nickell and Atkinson, 1995; Bromley 1996). Thalassinid

shrimp display deposit feeding, filter/suspension feeding, drift catching and omnivorous scavenging feeding behaviours (Griffis and Suchanek, 1991; Astall *et al.*, 1997). Such endobenthic shrimp efficiently control the oxygenation of their burrows, and can have inhalant and exhalant openings which produce conical mounds and funnel-shaped depressions at the sediment-water interface (Table 4.1; Ziebis *et al.*, 1996; Astall *et al.*, 1997). Burrow irrigation by thalassinid shrimps also has the additional benefit of introducing particulate matter to the burrow for suspension feeding (Pryor, 1975; Astall *et al.*, 1997).

Most modern studies of burrowing shrimps that produce *Thalassinoides*-like burrows are from marginal to shallow marine settings, in particular shallow bays, intertidal to subtidal flats, and estuaries (Table 4.1). Research into water depths of modern thalassinid shrimp burrows range from the upper intertidal to 15 m below mean sea-level, and burrows are commonly 9-24 mm in diameter, and infaunal tiering depths are 7-80 cm (Griffis and Chavez, 1988; Ziebis *et al.*, 1996; Astall *et al.*, 1997; Gingras *et al.*, 2001; Table 4.1). Thalassinids are also efficient sediment reworkers and can extrude 18 ± 9 ml of wet sediment per day (Swinbanks and Luternauer, 1987).

Neotrypaea and *Ubogebia* are recognized as bioturbators that have the ability to penetrate softground and firmground deposits (Pemberton and Frey, 1985; Gingras *et al.*, 2001, 2004). The burial time of a softground mud to become a firmground has been estimated at a "few years", when buried at a depth of at least 0.5 m (Yang *et al.*, 2009). *Thalassinoides* are also found in log-grounds in modern estuarine settings, and are produced by a mud shrimp (Gingras *et al.*, 2001, 2004). Modern marginal marine *Thalassinoides*-like burrows have been found to not change as burrows penetrate from

softground sand veneer, through a firmground mud and into a "woodground" (Gingras *et al.*, 2004). The implication of this observation is that firmground *Thalassinoides* may be unrelated to a key sequence stratigraphic surface. The colonization surface maybe associated with an overlying surface, potentially up to 80 cm stratigraphically above (Table 4.2). Firmgrounds that are not exposed at the seafloor at time of burrowing are known as concealed firmgrounds (Bromley, 1990). As in ancient examples of *Thalassinoides*-dominated surfaces, modern analogues are commonly found to be related to hiatal surfaces created by autocyclic- or allocyclic-induced erosion (Gingras *et al.* 2001, 2004; Yang *et al.* 2009), but are also a normal intrinsic component of estuaries.

4.3 *Thalassinoides* in ancient shallow water environments

The fill of *Thalassinoides* is commonly found to correspond to that of the lithology overlying the colonization surface to which the burrow is associated. For this reason *Thalassinoides* are easily identified in core and outcrop, and colonize a variety of substrates including softgrounds (*Cruziana* ichnofacies), and firmgrounds (*Glossifungites* ichnofacies).

The first occurrence of *Thalassinoides* comes from the Ordovician, and ranges through to the recent (Sheehan and Schiefelbein, 1984; Ekdale and Bromley, 2003; Buatois *et al.*, 2007). *Thalassinoides* is well known from both siliciclastic and carbonate rocks, and is most common from the Triassic to Recent (Table 4.2; Kamola *et al.*, 1984; Pemberton and MacEachern, 1995; Zeibis *et al.*, 1996; Gingras *et al.*, 2001; Miller and

Curran, 2001; Curran and Martin, 2003; Cunnningham *et al.*, 2009). In siliciclastic facies, *Thalassinoides* are recognized in a broad range of depositional environments from marginal-marine estuarine facies to marine turbidite facies, but are most common in shallow marine facies (e.g., Buatois *et al.*, 2007; Uchman, 1995; Phillips *et al.*, 2011). A deep water *Glossifungites* surface has been recognized by Savrda (2001), and interpreted as a firmground produced by transgression-induced sediment starvation (MacEachern and Burton, 2000).

A wealth of literature exists on sandstone/shell/pebble filled *Thalassinoides* burrows in mudstones (e.g., Table 4.2; Bromley, 1975; Pemberton and MacEachern, 1995; Gingras *et al.*, 2002). Where such coarse-grained burrow fills are uncompressed in mudstones, they are commonly inferred to be associated with firmground development, and are referred to colloquially as "*Glossifungites* surfaces" or more properly as omission or hiatal surfaces (Frey and Seilacher, 1980; Bromley, 1990; MacEachern *et al.*, 2007a; Table 4.2). These surfaces have been variously used to recognize the following sequence stratigraphic surfaces: sequence boundaries (SB); parasequence boundaries (pSB), transgressive surfaces of erosion (TSE); and flooding surfaces (FS) (e.g., Table 4.2; Taylor and Gawthorpe, 1993; Savrda *et al.*, 2001; Gingras *et al.*, 2002).

In carbonate shelf to slope facies, *Thalassinoides* has been recognized in chalk-marl successions at surfaces interpreted as omission surfaces where firmground and hardgrounds are inferred to have developed due to seafloor cementation/lithification (Bromley, 1967, 1975; Pemberton and Gingras, 1995; Locklair and Savrda, 1998; Table 4.2). Diagenetic enhancement (differential cementation) of *Thalassinoides* in carbonate facies (chalk, marls, dolomite and micrite) can be interpreted as early digenesis associated

with non-deposition (Bromley, 1967), and are associated with allocyclic generated sediment starvation (Table 4.2). Preservation of burrows can be enhanced or obscured by diagenesis. Four types of diagenetic burrow preservation have been described in carbonate facies: 1) preferred tube cementation; 2) preferred burrow cementation; 3) fabric-mimicking cementation, and 4) nodular hypo-burrow cementation (Gingras *et al.*, 2007).

The Bernoulli effect created by the open burrow morphology of *Thalassinoides* is thought to improve circulation through the burrow, also predisposing the burrow to post-mortem or post-abandonment infill from the sediment water interface (Vogel, 1981; Allanson, *et al.*, 1992). The burrow fill is generally the same as the grain size of sediment present at the sediment water interface at the time of burial. However, if the burrow remains open for some time—and hydrodynamic conditions change—the burrow fill may be composed of an erosional lag to a subsequent event unrelated to conditions at the time of occupancy of the burrow (Figure 4.2). *Thalassinoides* are often only clearly visible where there is lithologic contrast between the host sediment and burrow fill; examples of sandstone-filled burrows in mudstone-rich beds are well documented (Table 4.2).

Many authors have noted that normal basinal processes can generate *Thalassinoides*-dominated surfaces in firmground settings in association with exhumation firmground muds by storm events, tidal scour, tidal channel incision, submarine canyon incision, and changes in sediment delivery or rate (e.g., Grimm and Föllmi, 1994; Savrda, 1995; Löwemark *et al.*, 2004; McIlroy, 2004a,b). Alternatively, a so called *Thalassinoides*-bearing key stratigraphic surface may not be a surface at all, but a product

of the trace-maker penetrating a concealed firmground, unconnected to a contemporaneous depositional surface (Bromley, 1990).

Thalassinoides are found in a range of marine facies (marginal marine to slope), a variety of substrate consistencies (softground to firmground) and lithologies (siliciclastic and carbonate). The abundance and range of this marine ichnotaxon, therefore casts doubt on the preference in literature to invoke allocyclic processes to explain bioturbated stratigraphic surfaces (e.g., firmground *Glossifungites* surfaces; Table 4.2).

4.4 Taphonomic expressions of *Thalassinoides*

The basic geological principle of cross-cutting relationships applies to trace fossils, and the study of taphonomy (preservation) of trace fossils is an integral part in deciphering of paleocommunity analysis and determining of colonization order (see review in Savrda, 2007). Taphonomic expressions of *Thalassinoides*, and the relationship to its enclosing sediment, can illustrate a key stratigraphic surface, and accompanying depositional history and environmental information can be extracted (Figure 4.1). The depositional history can be broken down into: 1) deposition of burrowed substrate and associated processes; 2) colonization of substrate by trace-making organism; 3) infilling of burrow and further depositional processes; and 4) burial and diagenesis (Figure 4.2). The pre-deposition ichnofabrics, have previously been described as the pre-event or post-omission suite (Bromley, 1975). There are many variables to this idealized model, and

there may be more than one hiatal surface and/or condensed section, at different times in the taphonomic process (Figure 4.2).

Summaries of autocyclic and allocyclic interpretations for each of the four taphonomic expressions of *Thalassinoides* are discussed. These interpretations are highly dependent on sedimentological context. Detailed description of each of the aforementioned taphonomic expressions of *Thalassinoides* were studied in the deltaic facies of the heterolithic Lajas Formation (Middle Jurassic), Neuquén Basin, Argentina; shoreface facies of the Ben Nevis Formation (Early Cretaceous), Jeanne d'Arc Basin, offshore Newfoundland; marginal marine facies of the Blackhawk Formation (Late Cretaceous), Book Cliffs, Utah; and supplemented with an literature example from the marginal marine facies of the Pebas Formation (Miocene), Peru (Gingras *et al.*, 2002).

4.4.1 Deposition of mudstone (deposition of burrowed substrate)

The autocyclic interpretations of a softground marine mudstone in marginal marine to slope facies are: 1) continuous fair-weather sedimentation; or 2) event bed deposition (Einsele and Seilacher, 1991). Autocyclic interpretations for the development of a firmground marine mudstone are: 1) exhumation by event bed deposition (Savrda *et al.*, 2001); or 2) non-deposition due to change in sediment delivery (e.g., delta lobe abandonment or channel avulsion; Roberts, 1997). Allocyclic interpretations of softground mud deposition are: 1) component of transgressive parasequence set; or 2) or regressive parasequence set. Allocyclic interpretations for firmground development are:

1) sub-aerial exposure due to relative sea-level rise or sediment deposition due to relative sea-level fall (e.g., HST, and SB/pSB), and 2) current agitation precluding deposition (e.g., exhumation by wave or tidal ravinement; TSE). The trace-maker then colonizes the mudstone, creating open burrows, ready to be passively infilled during the next depositional event (Figure 4.2).

4.4.1.1 Infilling of burrows by sandstone deposition (mudstone: sandstone)

The open *Thalassinoides* are infilled with sandstone, usually producing a distinct lithologic contrast in the substrate (Figure 4.3A). The taphonomic expression of sandstone burrow fill, enclosed within firmground mudstone is commonly refereed to as being linked to a "*Glossifungites* surface". Possible autocyclic interpretations of such surfaces are: 1) event bed deposition and, 2) overprinting of ichnofabrics; or 3) change in sediment delivery (e.g., delta lobe switching or channel migration). The allocyclic interpretations for the same surface are: 1) transgressive surface of erosion (TSE); or 2) flooding surface (FS); or 3) amalgamated surface (SB and TSE); or 4) progradation of shoreface sands over offshore muds during regression (Figures 4.3A and 4.4).

4.4.1.2 Infilling of burrows by mudstone deposition (mudstone: mudstone)

Open *Thalassinoides* can be infilled with mudstone, producing a subtle lithologic contrast in the substrate (Figure 4.3B). The autocyclic interpretations of this subtle fabric are: 1) continuous softground development or event bed deposition of mud; and 2) overprinting of ichnofabrics. The allocyclic interpretations for the same fabric are: 1)

parasequence boundary (pSB); 2) flooding surface (FS; e.g., juxtaposition of offshore mudstone on nearshore mudstone); or 3) amalgamated surface (SB and FS); or 4) aggradation during transgression (Figures 4.3B and 4.4).

4.4.2 Deposition of sandstone (deposition of burrowed substrate)

Deposition of the "pre-omission" or "pre-event" sandstone is typically generated by autocyclic processes. The autocyclic interpretations of a softground marine sandstone in marginal marine to slope facies are either: continuous fair-weather sedimentation, or event bed deposition. The allocyclic interpretations of a softground marine sandstone in marginal marine to slope facies are: 1) related to relative sea-level rise (e.g., TSE, pSB, FS); or 2) relative sea-level fall (e.g., SB). The trace-maker then colonizes the sandstone, creating open burrows, ready to be passively infilled during the next depositional event.

4.4.2.1 Infilling of burrows by mudstone deposition (sandstone: mudstone)

Open *Thalassinoides* infilled with mudstone, produce a distinct lithologic contrast in the substrate (Figure 4.3C). The autocyclic interpretations of this preservation style are: 1) fair weather deposition of mud or event bed deposition; and 2) overprinting (colonization of historical layer from overlying sediment-water interface; or 3) change in sediment delivery (e.g., delta lobe switching or channel migration). The allocyclic interpretations for the same surface are: 1) flooding surface (FS; e.g., juxtaposition of offshore mudstone over shoreface sandstone during transgression); 2) parasequence boundary (pSB); and 3) amalgamated surface (pSB and FS; Figure 4.3C).

4.4.2.2 Infilling of burrows by sandstone deposition (sandstone: sandstone)

The open *Thalassinoides* are infilled with sandstone, producing a subtle lithologic contrast in the substrate (Figure 4.3D). The autocyclic interpretations of this subtle fabric are: 1) softground continuation or event bed deposition; and 2) overprinting of ichnofabrics. The allocyclic interpretations for the same fabric are: 1) transgressive surface of ersion (TSE); 2) parasequence boundary (pSB); 3) amalgamated surface (SB and FS); or 4) aggradation during transgression (Figures 4.3D).

4.4.3 Summary of taphonomic expressions of *Thalassinoides*

Thalassinoides-bearing surfaces, *Thalassinoides*-dominated ichnofabrics and "*Glossifungites* surfaces" are produced by a range of allocyclic and autocyclic-induced mechanisms. These four taphonomic expressions are not solely associated with firmgrounds or key sequence stratigraphic surfaces. The subtle expressions of mudstone-filled burrows in mudstone and sandstone-filled burrows in sandstone (Figures 4.3B and 4.3D) are generally attributable to autocyclically generated processes on softgrounds, including continuous quiescent deposition. These expressions of *Thalassinoides* would likely be overlooked in the rock record, and an autocyclic interpretation applied to the ichnofabric, although allocyclic interpretations may be just as valid (Figure 4.4).

Expressions of *Thalassinoides* preservation with distinct lithologic contrasts, can have either auotcyclic or allocyclic interpretations (Figures 4.2, 4.3A, 4.3C, 4.4, 4.5A, 4.5B), including ichnological overprinting (condensed and amalgamated beds), change in

substrate consistency, colonization/penetration from overlying surface, parasequence boundaries, sequence boundaries (SB), flooding surfaces (FS), transgressive surfaces (TS) and amalgamated surfaces (e.g., SB/TS). It is clear when studying all four taphonomic expressions of *Thalassinoides*, that there is a preservational biases towards burrows with distinct lithlogic contrast, and this is clear from the over representation in literature of the *Glossifungites* ichnofacies, i.e., sandstone-filled burrows within mudstone or coal beds (Table 4.2).

4.5 Examples of the *Thalassinoides*-bearing surfaces

The preservation (taphonomy) of *Thalassinoides* yields detailed data on depositional history, which can be interpreted in an autocyclic or sequence stratigraphic (allocyclic) context (Figure 4.2 and Table 4.2). *Thalassinoides*-bearing surfaces from the case studies and published literature are used as examples of both autocyclic and allocyclic interpretations for each taphonomic expression.

4.5.1 Sandstone-filled *Thalassinoides* in mudstone ("*Glossifungites* surfaces")

The first taphonomic expression is extremely conspicuous throughout the rock record, and is often referred to as a "*Glossifungites* surface" (*sensu* Pemberton and MacEachern, 1995). *Thalassinoides* are commonly, passively filled with light colored sandstone enclosed in dark colored mudstone (Figure 4.3A). Several examples of this

taphonomic expression have been studied from marginal marine settings of Permian to Miocence in age (Table 4.2). The majority of interpretations of this *Thalassinoides*-bearing key surface are allocyclically-based, sequence stratigraphic surfaces (e.g., TSE or SB; Table 4.2 and Figure 4.4).

Examples of *Thalassinoides* from the shoreface facies of the Ben Nevis Formation are sandstone-filled burrows in mudstone bed and interpreted to be formed by autocyclic mud event bed deposition (Figure 4.5A). Fluid mud deposition formed by enhanced settling velocity during wave dissipation or slack tidal currents (MacQuaker *et al.*, 2010), creating a softground substrate for colonization. The laminated mudstone bed in the Ben Nevis Formation is interbedded with bioturbated sandstone, and also contains other pipe-working forming burrows of *Planolites* and *Chondrites* (Figure 4.5A; Tonkin *et al.*, 2010). The post-event burrows are then infilled by sand during the return of fair-weather conditions on the wave-dominated shoreface.

The Blackhawk Formation, Book Cliffs, Utah contains abundant sandstone-filled *Thalassinoides* in carbonaceous mudstone, and is part of a marine to non-marine succession (Figure 4.3A). The carbonaceous bed interpreted as a coastal plain facies was deposited during a transgression, the increase in relative sea-level providing the accommodation space for carbonaceous mudstone development and preservation (Dubiel, 2003). A significant hiatal period followed peat deposition, and represents the shoreline regression, allowing for the development of a marine firmground surface. Subsequent erosion of mudstone and colonization by the *Thalassinoides* reflects a return to marginal marine conditions, and the onset of transgression. These open burrows are then filled with sandstone, associated with deposition of the overlying tidal channel facies (Kamola,

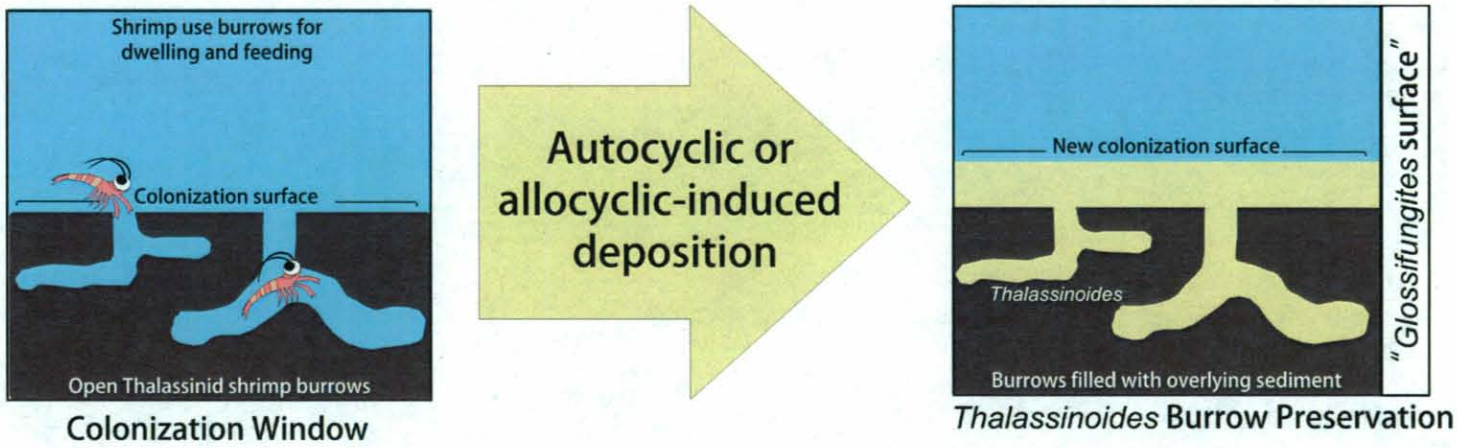


Figure 4.4. Schematic interpretation of the creation of a sand-filled *Thalassinoides* in mudstone ("*Glossifungites* surfaces") in a idealized shallow marine depositional setting. Several possible autocyclic and allocyclic interpretations can be drawn from this *Thalassinoides*-bearing surface. Autocyclic interpretations include: 1) event bed deposition, or 2) change in sediment delivery (e.g. delta lobe switching or channel migration). Allocyclic interpretations include: 1) transgressive surface of erosion (TSE), 2) parasequence boundary (pSB), or 3) amalgamated surface of a sequence boundary (SB) and transgressive surface of erosion (TSE).

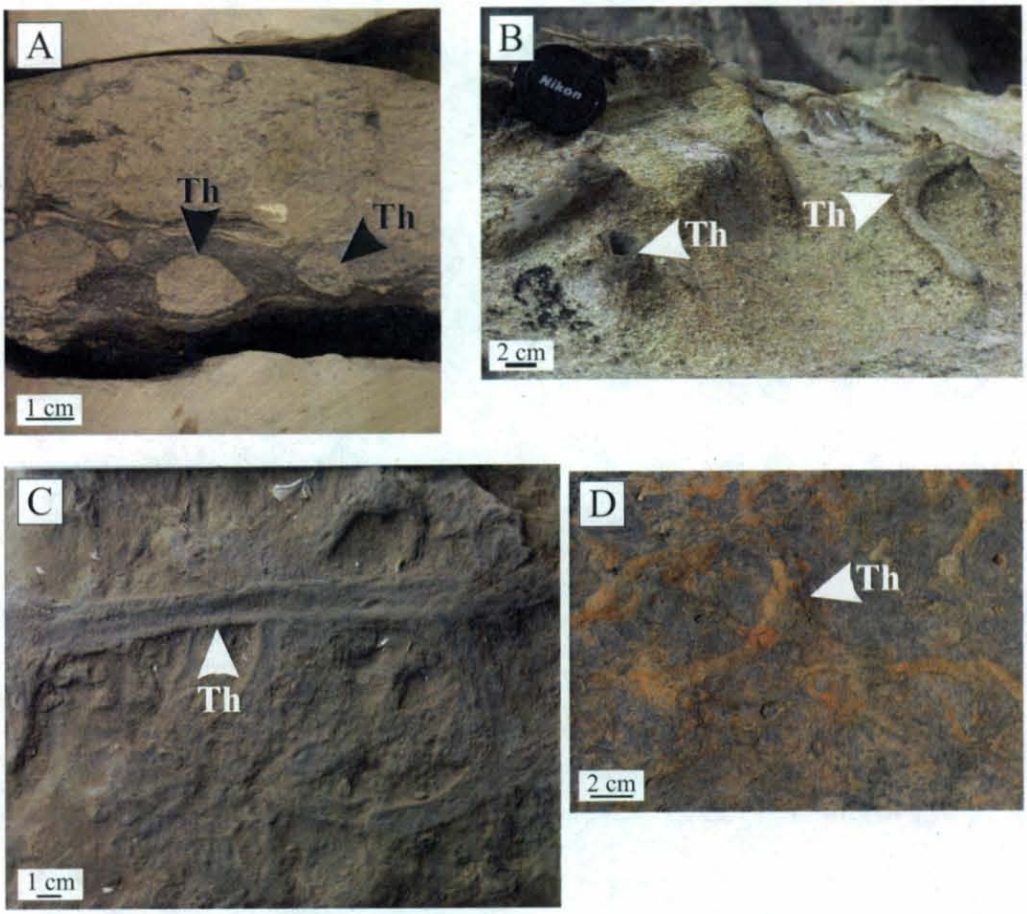


Figure 4.5. Examples of *Thalassinoides*-bearing surfaces. **A)** Sandstone-filled burrow in mudstone bed, from the shoreface facies of the Ben Nevis Formation, offshore Newfoundland, Canada. Fluid mud is colonized by trace-maker post-event, and infilled by sand (autocyclic interpretation). **B)** Mudstone-filled *Thalassinoides* in coarse-grained tuff from the Paeoneone Formation, New Zealand. An excellent example of the pipe-work building style of *Thalassinoides,* recolonizing the seafloor post-event deposition (autocyclic interpretation). **C)** Subtle lithological contrast of mudstone-filled *Thalassinoides* burrow in burrow-mottled muddy sandstone of the Paeoneone Formation. This ichnofabric characterizes softground conditions, associated with low sedimentation rates in the offshore zone (autocyclic interpretation). **D)** Sandstone-filled *Thalassinoides* in mudstone bed, from the deltaic facies of the Lajas Formation, Argentina. Interpreted as a transgressive surface of erosion (TSE).

1984; Figure 4.3A). Burrows are adhered to a bounding discontinuity surface that is laterally extensive in outcrop. This surface between the mudstone bed and tidal channel fill facies was allocyclically-induced and represents a sequence boundary (SB). The *Thalassinoides*-dominated ichnofabric (condensed bed), as a whole represents a sequence boundary (SB, basal contact of bioturbated bed, Figure 4.3A), and transgressive surface of erosion (TSE), where the firmground carbonaceous bed (developed during sediment starvation) was exhumed and colonized during the onset of transgression (Zaitlin *et al.*, 1994). This marginal marine ichnofabric is also termed the *Glossifungites* ichnofacies, or surface (MacEachern *et al.*, 2007a). It is conceivable burrows may be unrelated to the stratigraphic surface between the two distinct facies, and be associated with colonization of a concealed firmgound/woodground from an overlying surface.

In the deltaic Lajas Formation, Argentina, sandstone-filled burrows are preserved in a mudstone bed with a oyster-rich shell lag (Figure 4.5D). This *Thalassinoides*-dominated ichnofabric and contemporaneous shell lag can be interpreted as a transgressive surface of erosion (TSE). Alternatively, the autocyclic interpretation is related to exhumation of a firmground by storm, or underflow-induced erosion on the distal delta front (McIlroy *et al.*, 2005). Although, the an autocyclic interpretation is more likely in this example, as the surface can be traced into deltaic topsets with shell-rich reefs.

4.5.2 Mudstone-filled *Thalassinoides* in mudstone

The subtle taphonomic expression of mudstone to mudstone *Thalassinoides*, are rarely recognized in the rock record. An example from the inner shelf facies of the Paeoneone Formation, New Zealand has burrows with mudstone-fill within muddy sandstone, and is interpreted as an autocyclic associated taphonomic expression (Figure 4.5C). In outcrop, burrows are visible in hyporelief, cross-cut a highly bioturbated ichnofabric, and are inferred to represent condensed beds and fair-weather deposition on the softground paleo-seafloor. The condensed bed is produced by repeated overprinting of infaunal communities, and low sedimentation rates (Figure 4.5C).

Mudstone-filled burrows in mudstone are recognized in the distal delta front facies of the Lajas Formation, Argentina, and is interpreted as allocyclic (Figure 4.3B). This ichnofabric is interpreted as a well-oxygenated, softground distal delta front facies, bioturbation intensity is high implying, slow sedimentation rates, and cross-cutting of earlier ichnofabrics (palimpsesting).

4.5.3 Mudstone-filled *Thalassinoides* in sandstone

Mudstone-filled *Thalassinoides* are enclosed in sandstone, and are rare in the literature despite being conspicuous (Table 4.2). A literature example from the bay-margin facies of the Pebas Formation, Peru show a complex *Glossifungites* ichnofacies association, including mudstone-filled *Thalassinoides* in sandstone bay-margin parasequences (Gingras *et al.*, 2002). Marginal marine sands were colonized and penetrated by open burrows, then subsequently in-filled by the overlying mudstone. The

surface between the sandstone and mudstone is interpreted as a transgressive surface of erosion (TSE) formed by wave and tidal ravinement, demarcating the base of a parasequence (Gingras *et al.*, 2002).

In a coarsening upward deltaic succession, Lajas Formation, Argentina, mudstone-filled burrows in sandstone are recognized at the boundary between 2 cycles of delta front deposition (Figure 4.3C). Sharp walled *Thalassinoides* colonize sands in the distal delta front facies, these burrows are then infilled by mud deposition at the base of the next upward coarsening delta front package. Either autocyclically or allocyclically induced mechanisms can be interpreted from this ichnofabric. The *Thalassinoides*-bearing surface demarcates a boundary between two parasequences, and mudstone deposition may be associated with a marine flooding surface (McIlroy *et al.*, 2005). Alternatively, allocyclic or intra-basinal processes drive deposition, from either rapid fluid mud deposition (c.f. Macquaker *et al.*, 2010), or are a product of sediment delivery change on the delta front, caused by delta lobe switching (Roberts, 1997).

*M*udstone-filled *Thalassinoides* within a coarse-grained volcaniclastic sediment gravity flow bed are recorded from the inner shelf facies of the Paeoneone Formation, New Zealand (Figure 4.5B). A purely allocyclic interpretation is described for this *Thalassinoides* ichnofabric in this shelfal facies. The reworked pyroclastic ash event bed is colonized by pipe-work building strategists (*Thalassinoides*), and upon return to fair-weather conditions is infilled with mudstone (Figure 4.5B). While, no *Thalassinoides* burrows were identified in the enclosing background mudstone at this particular locality, further up-section mudstone in mudstone taphonomic expressions are visible in hyporelief (Figure 4.5C).

4.5.4 Sandstone-filled *Thalassinoides* in sandstone

Low contrast examples of *Thalassinoides* in sandstone are not commonly described, although large thin slice images of core slabs reveal they may be more common in sandstones than previously documented (Chapter 2, Figure 2.3; Tonkin *et al.* 2010). Subtle expressions of sandstone-filled *Thalassinoides* in sandstone of the Ben Nevis Formation and Lajas Formation are interpreted as autocyclic background sedimentation in the lower shoreface, and delta front, respectively (Figure 4.3D).

4.6 Discussion

There are variety of taphonomic expressions of *Thalassinoides* in siliciclastic rocks (Figures 4.2, 4.3 and 4.4). Four have been documented in the author's research and literature. The two most conspicuous taphonomic expressions relate to lithologic and grain size contrasts, for example: 1) sandstone-filled burrow in mudstone host rock; and 2) mudstone-filled burrow in sandstone filled host rock; but the more subtle; 3) sandstone-filled burrow in sandstone; and 4) mudstone-filled burrow in mudstone are less conspicuous in the rock record, and not well documented. There is a bias in literature towards a predominantly allocyclic or sequence stratigraphic interpretation of *Thalassinoides*-bearing bioturbated surfaces (Table 4.2), although it is clear that

autocyclic interpretations of the same surface may in some cases be equally valid (Figure 4.2).

The bioturbated key surfaces can be broken down into six components: 1) sandstone or mudstone deposition and formation of physical sedimentary structures; 2) bioturbation, formation of biogenic structures; 3) no hiatus, or hiatus and creation of firmground or condensed softground; 4) colonization of the substrate by *Thalassinoides* and creation of an open burrow; 5) infilling of the burrow by overlying or bypassing sandstone or mudstone and; 6) diagenesis and burial, which may include compaction, mineral replacement, cementation and degradation of organic matter. At each stage, a variety of physical environmental and ecological controls are active (Figures 4.1 and 4.2).

Interpretations of *Thalassinoides*-bearing surfaces can be attributed to either autocyclic processes such as storm-induced event sedimentation, or regressive or transgressive shoreline shift (Figure 4.4). Parasequence boundaries are often marked by "*Glossifungites* surfaces" and are interpreted as transgressive surfaces of erosion (TSE; e.g., Pebas Formation, Gingras *et al.*, 2007; Blackhawk Formation). Alternatively the "*Glossifungites* surface" (sandstone:mudstone) and mudstone: sandstone expressions may be bioturbated concealed firmgrounds (e.g., Blackhawk Formation, Figure 4.3A), fluid mud deposition (e.g., Ben Nevis Formation, Figure 4.5A) or storm induced erosion (e.g., Lajas Formation, Figure 4.5D). Rarely documented mudstone-filled *Thalassinoides* in sandstone may be associated with transgression, as flooding surfaces (e.g., FS; Lajas Formation, Figure 4.3D); transgressive surfaces of erosion (TSE; Pebas Formation), or post-event colonization (Paeoneone Formation, Figure 4.5B). Burrows with low lithologic contrast (e.g., Ben Nevis Formation, Figure 4.3D; Paeoneone Formation, Figure

4.5C) are generally interpreted as condensed beds, and can be attributed to variation in sedimentation rates associated with varying hydrodynamic energy in shallow marine facies. In the delta front facies of the Lajas Formation all possible four taphonomic are expressed and can associated with allocyclic processes including delta lobe switching, and change in sediment delivery at the distal delta front (mudstone-fill in sandstone).

The abundance of firmground mudstones in estuaries (Buatois *et al.*, 2005), means that the *Glossifungites* ichnofacies is likely to form without association to allocyclic key surfaces. Relating the *Glossifungites* firmground directly to relative sea-level change should be accepted only once alternative autocyclically generated processes are excluded. The implication of this conceptual study is the over-interpretation of bioturbated surfaces as sequence stratigraphic surfaces, in particular misidentification of systems tracts in core is possible. In core analysis where recognition of the laterally extent stratigraphic surface is not possible, alternate allocyclic interpretations must be considered. The majority of stratigraphic surfaces are most likely not associated with relative sea-level change, but a product of autocyclically controlled physical processes such as change in sediment delivery, and event bed deposition.

4.7 Conclusion

While this study has focused upon generalities, in each case study should be considered in its full sedimentological context as part of a succession of rocks. When a *Thalassinoides*-bearing surface is considered in its proper sedimentological, stratigraphic,

temporal and spatial context, it may be possible to favor either an autocyclic or an allocyclic controlling mechanism. Several possible auto/allocyclic interpretations can be drawn from each taphonomic expression of *Thalassinoides* (Figures 4.2, 4.3, 4.4 and 4.5).

Through a depositional step-by-step breakdown of the creation of a bioturbated key surface, the complexity of these surfaces is revealed. Multiple scenarios and interpretations can be commonly made. Non-unique solutions and interpretations of *Thalassinoides* ichnofabrics or *Glossifungites* ichnofacies may be extracted with understanding of stratigraphic and sedimentological context. Objective analysis of bioturbated key stratigraphic surfaces is an excellent tool for paleoenvironmental studies and reservoir characterization.

References

Allanson, B.R., D. Skinner, and J. Imberger, 1992, Flow in prawn burrows: Estuarine, Coastal and Shelf Science, v.35, p. 253-266.

Astall, C.M., A.C. Taylor, and R.J.A. Atkinson, 1997, Behavioral and physiological implications of a burrow-dwelling lifestyle for two species of upogebiid mud-shrimp (Crustacea: *Thalassinidea*): Estuarine, Coastal and Shelf Science, v. 44, p. 155–168.

Bromley, R. G., 1967, Some observations of Thalssinidean crustaceans in chalk hardgrounds: Journal of the Geological Society of London, v. 123, p. 157-182.

Bromley, R.G., 1975, Trace fossils at omission surfaces, *in* Frey, R.W., ed., The study of trace fossils; a synthesis of principles, problems, and procedures in ichnology: New York, United States, Springer-Verlag, p. 399-428.

Bromley, R.G., 1990, Trace fossils: biology and taphonomy: London, Unwin Hyman, 280 pp.

Bromley, R.G., 1996, Trace fossils: biology, taphonomy and applications: London, Unwin Hyman, 361 pp.

Bromley, R.G., and R.W. Frey, 1974, Redescription of the trace fossil *Gyrolithes* and taxonomic evaluation of *Thalassinoides*, *Ophiomorpha* and *Spongeliomorpha*: Bulletin of the Geological Society of Denmark, v. 23, p. 311-335.

Buatois L.A., R.G. Netto, and M.G., Mangano, 2007, Ichnology of Permian marginal- to shallow-marine coal-bearing successions: Rio Bonito and Palermo Formations, Parana basin, Brazil, *in* J. A. MacEachern, K. L. Bann, M. K. Gingras, and G. S. Pemberton, eds., Applied Ichnology: SEPM Short Course Notes 52, p. 167-177.

Catuneanu, O., 2006, Principles of sequence stratigraphy: Amsterdam; Boston, Elsevier, 375 pp.

Catuneanu, O., V. Abreu, J.P.Bhattacharya, M.D. Blum, R.W. Dalrymple, P.G. Eriksson, C.R. Fielding, W.L. Fisher, W.E. Galloway, M.R. Gibling, K.A. Giles, J.M. Holbrook, R. Jordan, C.G.St.C. Kendall, B. Macurda, O.J. Martinsen, A.D. Miall, J.E. Neal, D. Nummedal, L. Pomar, H.W. Posamentier, B.R. Pratt, J.F. Sarg, K.W. Shanley, R.J. Steel, A.,Strasser, M.E. Tucker, and C. Winker, 2009, Towards the standardization of sequence stratigraphy: Earth-Science Reviews, v. 92, p. 1–33.

Cummins, H., E.N. Powell, R.J. Stanton, and G. Staff, 1986, The rate of taphonomic loss in modern benthic habitats: how much of the potentially preservable community is preserved?: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 52, p. 291-320.

Cunningham, K.J., M.C. Sukop, H. Huang, P.F. Alvarez, H.A. Curran, R.A. Renken, and J. F. Dixon, 2009, Prominence of ichnologically influenced macroporosity in the karst Biscayne Aquifer: stratiform "super-K" zones: Geological Society of America Bulletin, v. 121, p. 164-180.

Curran, H.A., and A.J. Martin, 2003, Complex decapod burrows and ecological relationships in modern and Pleistocene intertidal carbonate environments, San Salvador Island, Bahamas: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 192, p. 229-245.

Dalrymple, R.W., 2010, Tidal depositional systems, *in* N.P James, and R.W. Dalrymple, eds., Facies Models 4: St John's, Geological Association of Canada, p. 201-231.

Dubiel, R.F., 2003, Summary of Geology and Coal Resources of the Blackhawk Formation in the Southern Wasatch Plateau, Central Utah, *in* M.A. Kirschbaum, L.N.R. Roberts, and L.R.H. Biewick, Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah: Denver, U.S. Geological Survey Professional Paper 1625–B, U.S. Department of the Interior, p. 1-26.

Ekdale, A.A., and R.G. Bromley, 2003, Paleoethologic interpretation of complex *Thalassinoides* in shallow-marine limestones, Lower Ordovician, southern Sweden: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 192, p. 221-227.

Einsele, G., and A. Seilacher, 1991, Distinction of tempestites and turbidites, *in* Einsele, G.,W. Ricken, and A. Seilacher, eds., Cycles and events in stratigraphy; basic concepts and terms: Berlin, Federal Republic of Germany, Springer Verlag, p. 377-382.

Einsele, G., W. Ricken, and A. Seilacher 1991, Cycles and events in stratigraphy; basic concepts and terms: Berlin, Federal Republic of Germany, Springer Verlag, 955 pp.

Frey, R.W., and A. Seilacher, 1980, Uniformity in marine invertebrate ichnology: Lethaia, v. 13, p. 183-207.

Frey, R.W., S.G. Pemberton, and T.D.A. Saunders, 1990, Ichnofacies and bathymetry; a passive relationship: Journal of Paleontology, v. 64, p. 155-158.

Fürsich, F.T., 1973, *Thalassinoides* and the origin of nodular limestone in the Corallian Bed (upper Jurassic) of southern England: Neues Jahrbuch für Geologie und Palaontologie, Monatshefte, v. 3, p. 136-156.

Fürsich, F.T., and Aberhan, M., 1994, Significance of time averaging for palaeocommunity analysis: Lethaia, v. 23, p. 143-152.

Gibert, J.M., and J.M. Robles, 2005, Firmground ichnofacies recording high frequency marine flooding events (Langhian transgression, Vales Penedes Basin, Spain): Geologica Acta, v. 3, p. 295-305.

Gingras, M.K., S.G. Pemberton, C.A. Mendoza, and F. Henk, 1999, Assessing the anisotropic permeability of *Glossifungites* surfaces: Petroleum Geoscience, v. 5, p. 349-357.

Gingras M.K., S.G. Pemberton, and T. Saunders, 2001, Bathymetry, sediment texture, and substrate cohesiveness: their impact: on modern *Glossifungites* trace assemblages at Willapa Bay, Washington: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 169, p. 1–21.

Gingras, M., M.E, Rasanen, S.G. Pemberton, and L.P. Romero, 2002, Ichnology and sedimentology reveal depositional characteristics of a bay-margin parasequences in the Miocene Amazonian foreland basin: Journal of Sedimentary Research, v. 72, p. 871-883.

Gingras, M.K., C.A. Mendoza, and S.G. Pemberton, 2004, Fossilized worm burrows influence the resource quality of porous media: AAPG Bulletin, v. 88, p. 875-883.

Gingras, M.K., G.S. Pemberton, F. Henk, J.A. MacEachern, C.A. Mendoza, B. Rostron, R. O'Hare, and M.V. Spila, 2007, Applications of ichnology to fluid and gas production in hydrocarbon reservoirs, *in* J.A. MacEachern, K. L. Bann, M.K. Gingras, and G.S. Pemberton, eds., Applied Ichnology: SEPM Short Course Notes 52, p. 131-145.

Gingras, M.K., S.E. Dashtgard, J.A. MacEachern, and S.G. Pemberton, 2008, Biology of shallow marine ichnology: A modern perspective: Aquatic Biology, v. 2, p. 255-268.

Griffis, R.B., and F.L. Chevez, 1988, Effects of sediment type on burrows of *Callianassa californiensis dana* and *C. gigas dana*: Journal of Experimental Marine Biology and Ecology, v. 117, p. 239-253.

Griffis, R.B., and T.H. Suchanek 1991, A model of burrow architecture and trophic modes in thalassinidean shrimp (*Decapoda*: *Thalassinidea*): Marine Ecology Progress Series, v. 79, p. 171-183.

Grimm, K.A., and Föllmi, K.B., 1994, Doomed pioneers: Allochthonous crustacean tracemakers in anaerobic basinal strata, Oligo-Miocene San Gregorio Formation, Baja California Sur, Mexico: Palaios, v. 9, p. 313-334.

Gowland, S., 1996, Facies characteristics and depositional models of highly bioturbated shallow marine siliciclastic strata; an example from the Fulmar Formation (Late Jurassic), UK Central Graben, *in* Hurst, A., H.D. Johnson, S.D. Burley, A.C. Canham, and D.S. Mackertich, eds., Geology of the Humber Group; Central Graben and Moray Firth, UKCS: Geological Society (London) Special Publication 114, p. 185-214.

Kamola, D.L., 1984, Trace fossils from marginal-marine facies of the Spring Canyon Member, Blackhawk Formation (Upper Cretaceous), East-Central Utah: Journal of Palaeontology, v. 58, p. 529-541.

Kidwell, S.M., and D.W.J. Bosence, 1991, Taphonomy and time-averaging of marine shelly faunas, *in* P.A., Allison and D.E.G. Briggs, eds., Taphonomy: relasing the

data locked in the fossils record: Topics in Geobiology 9, New York, Plenum Press, p. 115-209.

Kidwell, S.M., and K.W. Flessa, 1996, The Quality of the Fossil Record: Populations, Species, and Communities: Annual Review of Earth and Planetary Sciences, v. 24, p. 433-464.

Kraywinkel, H., and H. Seyfried, 1996, Sedimentologic, palaeoecologic, taphonomic and ichnologic criteria for high-resolution sequence analysis: a practical guide for the identification and interpretation of discontinuities in shelf deposits: Sedimentary Geology, v. 102, p. 79-110.

Locklair, R.E., and C.E. Savrda, 1998, Ichnofossil tiering analysis of a rhythmically bedded chalk-marl sequence in the Upper Cretaceous of Alabama: Lethaia, v. 32, p. 311-321.

Löwemark, L., J. Schonfeld, F. Werner, and P. Schäfer, 2004, Trace fossils as a paleoceanographic tool: evidence from Late Quaternary sediments of the southwestern Iberian margin: Marine Geology, v. 204, p. 27-41.

MacEachern, J.A., and J.A. Burton, 2000, Firmground *Zoophycos* in the Lower Cretaceous Viking Formation, Alberta: A distal expression of the *Glossifungites* Ichnofacies: Palaios, v. 15, p. 387-398.

McEachern, J.A., and S.G. Pemberton, 1992, Stratigraphic applications of the Glossifungites Ichnofacies: delineating discontinuities in the rock record, *in* S.G. Pemberton, ed., Applications of ichnology to petroleum exploration - a core workshop: SEPM Core Workshop 17, p. 169–198.

MacEachern, J.A., M.K. Gingras, K.L. Bann, S.G. Pemberton, 2007a, The ichnofacies paradigm: high-resolution paleoenvironmental interpretation of the rock record, *in* J.A. MacEachern, S.G. Pemberton, M.K. Gingras, and K.L. Bann, eds., Applied Ichnology: SEPM Core Workshop 52, p. 27–65.

MacEachern, J.A., M.K. Gingras, K.L. Bann, S.G. Pemberton, and L.T. Reich, 2007b, Applications of ichnology to high-resolution genetic stratigraphic paradigms, *in*: J.A. MacEachern, S.G. Pemberton, M.K. Gingras, and K.L. Bann, eds., Applied Ichnology: SEPM Core Workshop 52, p. 95–131.

Macquaker, J.H.S., S.J. Bentley, and K.M. Bohacs, 2010, Wave-enhanced sediment-gravity flows and mud dispersal across continental shelves: reappraising sediment transport processes operating in ancient mudstone successions: Geology, v. 38, p. 947-950.

McIlroy, D. 2004a, A review of ichnological concepts, methodologies, applications and frontiers, *in* D. McIlroy, ed., The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society (London) Special Publication 228, p. 3-27.

McIlroy, D., 2004b, Ichnofabrics and sedimentary facies of a tide-dominated delta; Jurassic Ile Formation of Kristin Field, Haltenbanken, offshore mid-Norway, *in* D. McIlroy, ed., The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society (London) Special Publication 228, p.237-272.

McIlroy, D., 2008, Ichnological analysis: The common ground between ichnofacies workers and ichnofabric analysts: Paleogeography, Paleoclimatology, Paleoecology, v. 270, p. 332-338.

McIlroy, D., S.S. Flint, J.A. Howell, and N.E. Timms, 2005, Sedimentology of the tide-dominated Jurassic Lajas Formation, Neuquén Basin, Argentina, *in* G.D. Veiga, L.A. Spalletti, J.A. Howell, and E. Schwarz, eds., The Neuquén Basin, Argentina; a case study in sequence stratigraphy and basin dynamics: Geological Society (London) Special Publication 252, p. 83-107.

McIlroy, D., and M. Garton, 2010, Realistic interpretation of ichnofabrics and palaeoecology of the pipe-rock biotope: Lethaia, v. 43, p. 420-426.

Martin, A.J., T.H. Rich, G.C.B. Poore, M.B. Schultz, C.M. Austin, L. Kool, and P. Vickers-Rich, 2008, Fossil evidence in Australia for oldest known freshwater crayfish of Gondwana: Gondwana Research, v. 14, p. 287-296.

Miller, M.F., and H.A. Curran, 2001, Behavioral plasticity of modern and Cenozoic burrowing thalassinidean shrimp: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 166, p. 219-236.

Mitchum Jr., R.M., P.R. Vail, and S. Thompson III, 1977, Seismic stratigraphy and global changes of se level, part II: the depositional sequence as a basic unit for stratigraphic analysis, *in*, Payton, C.E., ed., Seismic stratigraphy applications to hydrocarbon exploration: AAPG Memoir 26, p. 53-62.

Nickell, L.A., and R.J.A. Atkinson, 1995, Functional morphology of burrows and trophic modes of three thalassinidean shrimp species, and a new approach to the

classification of thalassinidean burrow morphology: Marine Ecology Progress Series, v. 128, p. 181-197.

Pemberton, S.G., R.W. Frey, M.J. Ranger, and J.A. MacEachern, 1992, The conceptual framework of ichnology, *in*, S.G., Pemberton, ed., Applications of ichnology to petroleum exploration; a core workshop: SEPM Core Workshop Notes 17, Tulsa, OK, p. 1-32.

Pemberton S.G., Frey R.W., 1985, The *Glossifungites* ichnofacies: modern examples from the Georgia Coast, USA, *in*, H.A., Curran, ed., Biogenic structures: their use in interpreting depositional environments: SEPM Special Publication 35, Tulsa, OK, p. 237-259.

Pemberton, S.G., and M.K. Gingras, 2005, Classification and characterizations of biogenically enhanced permeability: AAPG Bulletin, v. 89, p. 1493-1517.

Pemberton, S.G., and J.A. MacEachern, 1995, The sequence stratigraphic significance of trace fossils: examples from the cretaceous Foreland Basin of Alberta, Canada, *in*, J.A. Van Wagoner, and G.T. Bertram, eds., Sequence Stratigraphy of Foreland Basin Deposits - Outcrop and Subsurface Examples from the Cretaceous of North America: AAPG Memoir 64, p. 429-475.

Pemberton, S.G., R.W. Frey, M.J. Ranger, and J.A. MacEachern, 1992, The conceptual framework of ichnology; Applications of ichnology to petroleum exploration; a core workshop: SEPM Core Workshop Notes 17, p. 1-32.

Phillips, C., D. McIlroy, and T. Elliot, 2011, Ichnological characterization of Eocene/Oligocene turbidites from the Grès d'Annot Basin, French Alps, SE France: Palaeogeography, Palaeoclimatology and Palaeoecology, v. 300, p. 67-83.

Pryor, W.A., 1975, Biogenic sedimentation and alteration of argillaceous sediments in shallow marine environments: Geological Society of America Bulletin, v. 86, p. 1244-1254.

Roberts, H.H., 1997, Dynamic changes of the Holocene Mississippi River delta plain; the delta cycle; Louisiana's barrier islands; an evaluation of their geological evolution, morphology and rapid deterioration: Journal of Coastal Research, v. 13, p. 605-627.

Savrda, C.E., 1995, Ichnologic applications in paleoceanographic, paleoclimatic, and sea-level studies: Palaios, v. 10, p. 565-577.

Savrda, C.E., J.V. Browning, H. Krawinkel, and S.P. Hesselbo, 2001, Firmground ichnofabrics in deep-water sequence stratigraphy, Tertiary clinoform-toe deposits, New Jersey slope: Palaios, v. 16, p. 294-305.

Schlirf, M., 2000, Upper Jurassic trace fossils from the Boulonnais (northern France): Geologica et Paleontologica, v. 34, p. 145-213.

Sheehan, P.M., and D.R.J. Schiefelbein, 1984, The trace fossil *Thalassinoides* from the Upper Ordovician of the eastern Great Basin: deep burrowing in the early Paleozoic: Journal of Paleontology, v. 58, p. 440-447.

Swinbanks, D.D., and J.L. Luternauer, 1987, Burrow distribution of thalassinidean shrimp on a Fraser Delta tidal flat, British Columbia: Journal of Paleontology, v. 61, p. 315-332.

Taylor, A.M., R. Goldring, and S. Gowland, 2003, Analysis and application of ichnofabrics: Earth-Science Reviews, v. 60, p. 227-259.

Taylor, A.M., and R.L. Gawthorpe, 1993, Application of sequence stratigraphy and trace fossils analysis to reservoir description; examples from the Jurassic of the North Sea, *in* J.R. Parker, ed., Petroleum geology of Northwest Europe: Proceedings of the 4th conference: The Geological Society, London, p. 317-335.

Tomer, A., T. Muto, and W. Kim, 2011, Autogenic hiatus in fluviodeltaic successions: geometrical modeling and physical experiments: Journal of Sedimentary Research, v. 81, p. 207-217.

Tonkin, N.S., D. McIlroy, R. Meyer, and A. Moore-Turpin, 2010, Bioturbation influence on reservoir quality: a case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada: AAPG Bulletin, v. 94, p. 1059-1078.

Twitchett, R.J., and C.C. Barras, 2004, Trace fossils in the aftermath of extinction, *in* D. McIlroy, ed., The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society (London) Special Publication 228, p. 397-418.

Uchman, A., 1995, Taxonomy and palaeoecology of flysch trace fossils: The Marnoso-arenacea Formation and associated facies (Miocene, Northern Apennines, Italy): Beringeria, v. 15, p. 3-115.

Valentine, J.W., and D. Jablonski, 1993, Fossil communities: Compositional variation at many time scales, *in,* R.E. Ricklefs, and D. Schluter, eds., Species diversity in ecological communities: historical and geographical perspectives: University of Chicago Press, p. 341-349.

Van Wagoner, J.C., H.W. Posamentier, R.M. Mitchum, P.R. Vail, J.F. Sarg, T.S. Loutit, and J. Hardenbol, 1988, An overview of sequence stratigraphy and key definitions, *in*, C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner, eds., Sea Level Changes—An Integrated Approach: SEPM Special Publication 42, p. 39–45.

Van Wagoner, J.C., R.M. Mitchum, K.M. Campion, and V.D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high resolution correlation of time and facies: Tulsa, OK, AAPG Methods in Exploration Series 7, 55pp.

Vogel, S., 1978, Organisms that capture currents: Scientific American, v.229, p.128-139.

Wanless, H.R., L.P. Tedesco, and K.M. Tyrrell, 1988, Production of subtidal tubular and surficial tempestites by Hurricane Kate, Caicos Platform, British West Indies: Journal of Sedimentary Petrology, v. 58, p. 739-750.

Yang, B.C., 2009, Autogenic occurrence of *Glossifungites* ichnofacies; examples from wave-dominated, macrotidal flats, southwestern coast of Korea: Marine Geology, v. 260, p. 1-5.

Zaitlin, B.A., R.W. Dalrymple, and R. Boyd, 1994, The stratigraphic organization of incised-valley systems associated with relative sea-level change, *in* R.W. Dalrymple, R. Boyd and B.A. Zaitlin, Incised-valley Systems: Origin and Sedimentary Sequences: SEPM Special Publication 51, p. 45-60.

Ziebis, W., S. Forber, M. Huettel and B.B. Jørgensen, 1996, Complex burrows of the mud shrimp *Callianassa* and their geochemical impact in the seabed: Nature, v. 382, p. 619-622.

Chapter 5: Summary - Bioturbation as a tool in reservoir characterization

In bioturbated reservoir facies, ichnology is integral to reservoir characterization. This research uses bioturbated shallow marine case studies to create a first order understanding of likely reservoir quality (Chapter 2), reservoir heterogeneity (Chapter 3), and interpretation of autocyclic or allocyclic (sequence stratigraphic) key surfaces (Chapter 4), that can be incorporated into reservoir to basin scale models of hydrocarbon reservoirs.

5. 1 Effect of bioturbation on reservoir quality

Description and interpretation of bioturbation in shallow marine facies is a valuable tool in reservoir characterization. Ichnological analysis of a reservoir facies and subsequent classification into ichnofabrics or ichnofacies allows for characterization of reservoir properties. In highly bioturbated reservoir facies, physical modification by trace fossils can be the first order control on petrophysical properties; e.g. if the bioturbated reservoir were quartz cemented, the cementation would be the first order control. The action of bioturbators can be classified in terms of: 1) sediment mixing; 2) sediment cleaning; 3) sediment packing; 4) pipe-work building strategies; 5) combination sediment cleaning and packing; and 6) combination pipe-work building and sediment packing (see Table 6.1). These categories of bioturbation style have predictable effects on porosity

Bioturbation Style	Description	Common Trace Fossils	Ichnofacies	Bioturbation Intensity	Substrate Consistency	Porosity (net effect)
Sediment Mixing	Indiscriminate mixing of sediment grains, decreasing the sorting of the sediment by un-sorting any grain-size trends. Sediment mixers burrow in the sediment without sorting the sediment into distinct burrow linings or fills.	Cryptobioturbation, *Macaronichnus* and burrow mottling.	*Skolithos*, *Cruziana*, and *Zoophycos*.	Moderate to intense (BI 4 to 5)	Softground	Reduce (commonly) or enhance .
Sediment Packing	Incorporation of fine-grade material (e.g., clay and fine organic matter) from the host sediment into burrow fills and/or linings; decreases sorting of the sediment.	*Asterosoma*, *Chondrites*, *Diplocraterion*, *Ophiomorpha*, *Palaeophycus*, *Phycosiphon*, *Scolicia*, *Teichichnus* and *Zoophycos*.	*Skolithos*, *Cruziana*, and *Zoophycos*.	Sparse to intense (BI 1 to 5)	Softground	Reduce
Sediment Cleaners	Selectively removing fine-grained material (e.g., pore-filling clay-silt and organic matter) from the sediment, increasing sorting of the sediment. By ingestion and subsequent defecation of fines into the water column; producing a current within the near-burrow environment; or packing of selected fine-grained material elsewhere in the burrow structure.	*Thalassinoides* and *Phycosiphon*.	*Skolithos*, *Cruziana*, and *Zoophycos*.	Sparse to intense (BI 1 to 5)	Softground	Enhance
Pipe-work Building	Open semi-permanent burrows in sediment perforate pre-existing physical sedimentary fabrics. Upon burrow abandonment, the burrow generally remains open and is passively filled with the overlying sediment at the sediment-water interface.	*Ophiomorpha, Planolites Skolithos*, *Gyrolithes*, *Psiloichnus, Arenicolites* and *Thalassinoides*.	*Glossifungites*, *Skolithos*, *Cruziana*, and *Zoophycos*.	Sparse to intense (BI 1 to 5)	Softground and firmground.	Enhance or reduce (dependent on lithological contrast)
Combination sediment cleaning & packing	Incorporation of finer grade material from the host sediment into burrow fills and/or linings, and cleaning of adjacent sediment.	*Phycosiphon*	*Skolithos*, *Cruziana*, and *Zoophycos*.	Sparse to intense (BI 1 to 5)	Softground	Enhance
Combination pipe-work building & sediment packing	Open burrows in sediment perforate pre-existing physical sedimentary fabrics, and pack finer grade material from the host sediment into burrow linings.	*Ophiomorpha*	*Glossifungites*, *Skolithos*, *Cruziana*, and *Zoophycos*.	Sparse to intense (BI 1 to 5)	Softground and firnground.	Enhance or reduce (dependent on lithological contrast)

Note: Each style has the net effect of permeability/porosity enhancement or reduction. These styles incorporate trace fossil morphology, presence or absence of burrow linings, and bioturbation intensity. The petrophysical characteristics of pipe-work building and combination bioturbation styles are highly dependent on the lithological contrast between burrow fill and enclosing/host substrate.

Table 6.1. Bioturbation Style categories in marine sediments (modified and updated from Tonkin et al., 2010).

and permeability, and can be easily incorporated into reservoir characterization, even by the non-expert.

5.2 Application of bioturbation styles as a tool to predict reservoir quality

Petroleum geologists are primarily concerned with the effect that bioturbation has on the petrophysical properties of a reservoir facies, rather than the details of ichnotaxonomic identification. The proposed bioturbation style categories do not require in-depth knowledge of ichnology. The categories can easily be applied to facies and core analysis for incorporation into reservoir models. This approach makes ichnofabric study accessible and directly applicable to reservoir characterization. Bioturbation can redistribute grains and cause sorting or mixing (see Chapter 2), this physical modification of the primary sedimentary fabric effects porosity and permeability in reservoir facies. The physical modification of the sediment by trace-making organisms has the potential to either decrease sorting, by un-sorting physically-sorted grains or increase sorting by direct manipulation of grains, and through creation of open burrow systems. The bioturbation style categories seen in a hydrocarbon reservoirs (Tonkin *et al.*, 2010), were introduced in Chapter 2, used in Chapter 3 and are further refined below (see Table 6.1).

1) Sediment mixing –indiscriminate mixing of sediment grains, decreases the sorting of the sediment by un-sorting any grain size trends, and through mechanical destruction of depositional textures. "Sediment mixers" burrow in the sediment without sorting the sediment into distinct burrow linings or fills (e.g. cryptobioturbation and

burrow mottling). These biogenic structures generally cannot be attributed to a specific ichnotaxa. This type of bioturbation by bulk sediment mixers commonly constitutes a large proportion of ichnofabrics (cf. Chapters 2 and 3). Localized sediment mixing style in laminated facies enhances porosity and permeability, through elimination of fine-grained laminae or pre-existing discrete traces (e.g. sediment packers) that act as baffles for fluid flow. Alternatively in burrow mottled fabrics (with high bioturbation intensities), the collective sediment mixing behavior of the trace-making organisms, and bulk sediment mixing /unsorting of grain size trends or bedding would reduce permeability/porosity. The net effect of sediment mixing style is most commonly porosity and permeability reduction.

2) Sediment packing – incorporation of finer grade material (e.g. clay, silt and fine-grained organic carbon) from the adjacent stratigraphic levels into burrow fills and/or linings decreases the sorting of the sediment. Packing of clay and silt-grade grains into pore space locally reduces permeability, relative to the adjacent substrate. Lined burrows (e.g. *Palaeophycus*), burrows that have been actively infilled by the trace maker (e.g. *Asterosoma*, *Chondrites*, *Diplocraterion*, *Phycosiphon*, *Scolicia*, *Teichichnus* and *Zoophycos*), can be categorized as "sediment packers". Tracemakers can also incorporate coarser grade material (e.g. sand and coarse tuff within a mudstone) from the adjacent stratigraphic levels into burrow fills and/or linings decreasing sorting of the sediment. The net effect of sediment packing style is most commonly porosity and permeability reduction.

3) Sediment cleaning – selective removal of fine-grained material (e.g., pore-filling clay-silt and organic matter) from the enclosing substrate, increasing sorting. By

ingestion and subsequent defecation of fines into the water column. Burrows with halos of well-sorted clean sands (e.g. *Thalassinoides*) are categorized as "sediment cleaners". The net effect of sediment cleaning style is permeability enhancement.

4) Pipe-work building – open semi-permanent burrows in sediment perforate pre-existing sedimentary fabrics or ichnofabrics. Such biogenic structures are connected to the sediment-water interface. Upon burrow abandonment, the burrow generally remains open and is passively filled with the overlying sediment at the sediment-water interface. Trace fossils of *Ophiomorpha*, *Planolites*, *Skolithos*, *Thalassinoides* and *Teredolites* are categorized as "pipe-work builders". The net effect of this bioturbation style is dependent on the lithological contrast between the burrow fill and the host sediment. For example, *Thalassinoides* in the Ben Nevis field are sandstone-filled burrows within thin mud beds that produce vertical and horizontal macropore networks, with the potential to act as flow conduits (Chapter 2; Tonkin *et al.*, 2010). This bioturbation style can be further subdivided into vertical or horizontal pipe-work building.

5) Combination sediment cleaning and packing – incorporation of finer grade material from the host sediment into burrow fills and/or linings, and cleaning of adjacent sediment. *Phycosiphon* burrows are an example of this combined bioturbation style, with their clay-grade core and coarser grained halo. The net effect of this combination bioturbation style is dependent on the lithological context, in particular the contrast between burrow fill and host substrate. For example, *Phycosiphon* halos have twice the volume of coarse-grained halo than the associated clay-rich burrow core, and therefore have the net effect of permeability enhancement in shale gas reservoirs (Bednarz and McIlroy, 2009).

Combination pipe-work building and sediment packing – open burrows in sediment perforate pre-existing physical sedimentary fabrics, and pack finer grade material from the host sediment or suspended sediment into burrow linings. *Ophiomorpha* burrows are an example of this combined style. Burrow margins are packed with mud, while the burrow itself remains open and is passively infilled with sediment. *Ophiomorpha* is distinct from other pipe-work building ichnotaxa (*Planolites*, *Skolithos*, and *Thalassinoides*) which are unlined. The net effect of this bioturbation style is dependent on the lithological contrast between burrow fill and host sediment.

Categorization of bioturbation style can be applied to any bioturbated reservoir facies, and used as a tool to predict reservoir quality (Table 6.1). Enhancement or reduction of porosity/permeability, is dependent on trace fossil morphology, composition of burrow linings/fills, burrow size, bioturbation intensity, and bioturbation style (Chapter 2). The petrophysical characteristics of pipe-work building and combination bioturbation styles are highly dependent on the lithological contrast between burrow fill, and enclosing substrate. Sediment packing and sediment mixing styles commonly reduce porosity/permeability, while sediment cleaning bioturbation style enhances porosity/permeability. An understanding of trace fossil behavior, as it affects reservoir quality is important in reservoir characterization. The use of bioturbation style categories and the classification of trace fossils into these categories may be a more useful application of ichnological analysis reservoir geologists, than paleoenvironmentally-driven ichnofacies or ichnofabric analyses.

5.3 Ichnological trends in reservoir heterogeneity

While categorization of bioturbation style is a useful tool in reservoir characterization, lateral variations in reservoir quality and heterogeneity of ichnofacies or ichnofabric must be incorporated into geological models in order to predict fluid flow in bioturbated facies at the inter-well scale (Chapter 4). Trends in trace fossil distribution are excellent indicators of in-situ spatial variability of physico-chemical processes. Ichnological analysis allows insight into variations in sedimentation rate, hydrodynamic energy (erosive currents), substrate consistency, length of colonization window, and community succession (tiering and cross-cutting relationships). The patchy distribution of endobenthic organisms on the modern seafloor is not directly comparable to patterns of spatial distribution in the ichnological record. Biological factors (e.g., larval dispersal, competition and predation) are unlikely to be contributing factors in controlling the benthic spatial distribution in the rock record. Time-averaging, community succession and physical processes of erosion and deposition on a geological timescale are likely to erase primary ecological signatures in most cases.

There is inherent ichnological variability within most beds. However if one considers only the effect on reservoir quality caused by bioturbators (bioturbation style), the net effect on reservoir quality heterogeneity is seen to be less variable than would first appear. Ichnofabrics most commonly result from bioturbation by several communities, effectively a condensed representation of an unknown number of communities (with hiatuses).

The variability, or patchiness, along-strike was not found to be related to proximity to the paleo-shoreline in the three wave-dominated depositional systems. Instead, the most critical factor appears to be the sediment accumulation style. Slow continuous deposition was found to produce complex and highly patchy ichnofabrics, whereas rapid, episodic, event bed deposition was found to be associated with the most uniform development of ichnofabric.

5.4 Identification of key stratigraphic surfaces in bioturbated facies

Identification of bioturbated hiatal or key stratigraphic surfaces of erosion, non-deposition or condensation are clearly identifiable where there is a distinct lithological contrast in burrow fill relative to the host sediment. Autocylic and allocyclic interpretations of key stratigraphic surfaces can be postulated for the pre-bioturbation and post-bioturbation in siliciclastic shallow marine settings. A case study illustrating the need for careful ichnological analyses has been undertaken as part of this thesis (see Chapter 4), and focuses on *Thalassinoides* burrows, and its validity as an indicator for key stratigraphic surfaces, and outline all applicable autocyclic and allocyclic processes.

Thalassinoides is easily identified in core and outcrop, has a pipe-work bioturbation style, and colonizes a variety of substrates including softground and firmground (*Glossifungites* ichnofacies) substrates. The *Glossifungites* firmground association with base level change, and transgression may be an over-interpretation, and alternative autocyclically-generated processes should be investigated. Uncritical use of the *Glossifungites* ichnofacies as a direct indicator for the identification of relative sea

level rise is considered to be flawed. Possible autocyclic mechanisms for formation of firmground surfaces should always be objectively considered. Four taphonomic expressions of *Thalassinoides* are described: 1) sandstone-filled burrow in mudstone host rock; 2) mudstone-filled burrow in mudstone; 3) mudstone-filled burrow in sandstone filled host rock; 4) sandstone-filled burrow in sandstone; and have been discussed in this thesis (Chapter 3). These interpretations of *Thalassinoides*-bearing surfaces are generic and could be applied to carbonate facies such as chalks, marls, calcarenites and shell beds; and extended to other pipe-work building ichnotaxa (e.g. *Ophiomorpha, Skolithos*, and *Planolites*). With careful ichnological investigation, realistic palaeoenvironmental and sequence stratigraphic interpretations can be made by objective consideration of both autocyclic and allocyclic processes.

5.5 Contributions of ichnology to reservoir characterization

Ichnological analysis is becoming an integral part of reservoir characterization. The petrophysical properties associated with bioturbation can be predicted (Chapter 2); spatial variability and heterogeneity can be determined in bioturbated reservoir facies (Chapter 3); and both autocyclic and allocyclic controls on ichnology can be incorporated into reservoir model (Chapter 4).

In bioturbated reservoir facies, the proposed bioturbation style categories (Tonkin *et al.*, 2010 and herein) can be incorporated into conventional facies and core analysis. Core can be logged and assigned bioturbation styles, allowing the petroleum geologist to

make predictions with respect to porosity/permeability trends, and define potential net pay intervals without needing to be a specialist ichnologist.

Ichnological variability in hydrocarbon reservoirs is dependent on sediment accumulation style. In depositional settings where there is slow continuous deposition, complex and highly patchy ichnofabrics are recognized. Where event bed sedimentation is the norm, ichnofabrics with very little change along-strike predominate in the event bed itself. If the petroleum geologist focuses on the effect of bioturbation on reservoir properties using bioturbation style categorization (rather than getting deeply involved in ichnotaxonomic variability), lateral variability in reservoir quality can be assessed. This work has found that while ichnodiversity commonly changes, the net effect on reservoir quality, and the bioturbational style, is seen to be less variable than it might first appear.

This thesis has shown that ichnology analysis (ichnofabric and ichnofacies) is a useful, and directly applicable tool for reservoir characterization. With an improved, integrated, understanding of what bioturbating organisms do to sediment, ichnology can continue to grow as an important component of reservoir characterization studies, and petroleum geology in general.

5.6. References

Bednarz, M., and D. McIlroy, 2009, Three-dimensional reconstruction of "phycosiphoniform" burrows: implications for identification of trace fossils in core: Palaeontologica Electronica, v. 12, 15p; http://palaeo-electronica.org/2009_3/195/index.html.

Tonkin, N.S., D. McIlroy, R. Meyer, and A. Moore-Turpin, 2010, Bioturbation influence on reservoir quality: a case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada: AAPG Bulletin, v. 94, p. 1059-1078.